ENGINEERING

MATERIALS

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NON-FERROUS AND ORGANIC MATERIALS

SECOND EDITION

PREFACE

THE present volume is a thoroughly revised and largely rewritten version of the previous edition of a work which was published originally in 1920. It is the second volume of a series of three, of which the first, dealing with the ferrous metals, was published in its latest revised form recently. The third volume covers the theory and testing of engineering materials.

The book is intended, primarily, for the engineer, designer, draughtsman, and others concerned with the selection and application of non-ferrous metals and certain organic materials used in engineering, e.g. plastics, artificial and natural rubbers, abrasives, ceramics, etc. It is intended as a useful guide and reference work both to the user of materials and to the student.

In the preparation of this edition the needs of the aircraft and automobile engineer have been given priority of consideration, but the more important requirements of the mechanical, constructional, and electrical engineer have also been considered.

In the present treatment no attempt has been made to give anything but a bare outline of the metallurgical and metallographical sides of the subject, since the book is intended for the engineering user who is concerned more with the mechanical and physical properties of materials and their practical applications.

In view of the increasing importance, in aircraft, automobile, and many other fields of light engineering, of the applications of strong light alloys, these metals have been given special attention and prominence in the present work. The more recent developments in connection with the use of plastics, plastic-bonded plywoods, and synthetic rubbers for various engineering purposes are also dealt with as fully as space considerations would allow.

In conclusion, the writer would like to record his appreciation of the assistance that has been generously accorded in the preparation of this volume by various firms, institutions, and individuals; in particular to The British Aluminium Company, Northern Aluminium Company, Copper Development Association, Mond Nickel Company, Messrs. F. A. Hughes, Ltd., High Duty Alloys, Ltd., Bakelite, Ltd., The Rubber Growers' Association, Ltd., International Tin Research and Development Council, Dr. W. H. Hatfield, and Dr. L. Aitchison.

<div align="right">A. W. JUDGE.</div>

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ENGINEERING MATERIALS

CHAPTER I

THE NON-FERROUS METALS AND THEIR ALLOYS

THERE is a wide range of non-ferrous metals employed for engineering purposes but, although the pure metals are occasionally used for certain applications, it is the alloys of these which have become of much greater importance in recent times, so that the greater part of the present volume is devoted to some general considerations of these alloys and their applications.

The physical and mechanical properties of the principal metals with which the engineer is concerned are given in Tables 1 and 2, and

TABLE 1

PHYSICAL PROPERTIES OF METALS

Metal	Atomic Weight O = 16	Specific Gravity	Weight per cub. in. lb.	Melting Point °C.	Thermal Conductivity Cal. per cm.³ °C per sec.	Specific Heat Cal. per gm. per °C.
Aluminium (H.D. wire)	27·1	2·703	0·0975	658·7	0·504	0·214
Antimony . . .	120·2	6·71	0·242	630	0·044	0·051
Bismuth . . .	208	9·9	0·357	269	0·019	0·031
Cadmium . . .	112·4	8·65	0·311	321	0·222	0·057
Cobalt . . .	58·97	8·6	0·310	1490	—	0·107
Copper (H.D. wire) .	63·6	8·89	0·320	1083	0·89	0·097
Gold (wrought) . .	197·2	19·4	0·700	1063	0·70	0·032
Iron (cast) . . .	- -	7·22 (av.)	0·260	1375	0·161	0·125
Iron (wrought) . .	55·84	7·70 (av.)	0·278	1550 (av.)	0·144	0·114
Lead	207·2	11·4	0·411	327	0·083	0·031
Magnesium . . .	24·32	1·74	0·0627	651	0·376	0·250
Mercury . . .	200·6	13·59	0·490	38·7	0·0197	0·033
Nickel . . .	58·68	8·85	0·312	1452	0·142	0·109
Palladium . . .	106·7	11·4	0·411	1549	0·168	0·052
Platinum (wrought) .	195·2	22·1	0·797	1755	0·166	0·032
Silver (wrought) . .	107·88	10·5	0·378	961	1·006	0·056
Steel (wire) . . .	—	7·84	0·282	1350 (av.)	0·115	0·117
Tantalum (wire) . .	181·5	16·6	0·598	2850	—	0·036
Tin (cast) . . .	118·7	7·29	0·263	232	0·155	0·054
Tungsten (wire) . .	184	19·1	0·689	3000	—	0·033
Zinc (sheet) . . .	65·37	7·19	0 259	419	0·265	0·092

[British Aluminium Co.]

TABLE 2

MECHANICAL AND ELECTRICAL PROPERTIES OF METALS

Metal	Coefficient of Linear Expansion per °C.	Modulus of Elasticity lb. per sq. in.	Tensile Strength lb. per sq. in.	Specific Resistance at 20° C. in microhms per cm.³	Coefficient of Increase of Resistance per °C.	Elec.-Chem. Equivalent gm. per amp. hr. and Change of Valency	
Aluminium (H.D. wire)	23×10^{-6}	$9 \cdot 9 \times 10^6$	23,000 to 33,000	2·85	0·00407	0·3369	
Antimony .	$10 \cdot 80 \times 10^{-6}$	—	—	40·50	0·00389	0·896	(5)
Bismuth .	$13 \cdot 90 \times 10^{-6}$	$4 \cdot 63 \times 10^6$	—	119·0	0·0042	2·586	(3)
Cadmium .	$30 \cdot 60 \times 10^{-6}$	$7 \cdot 24 \times 10^6$	—	7·54	0·0040	2·096	(2)
Cobalt . .	$12 \cdot 30 \times 10^{-6}$	—	—	9·71	0·0033	1·100	(2)
Copper (H.D. wire)	$16 \cdot 60 \times 10^{-6}$	18×10^6	55,000 to 63,000	1·77	0·003999	1·186	(2)
Gold . .	$13 \cdot 90 \times 10^{-6}$	$11 \cdot 58 \times 10^6$	20,000 to 30,000	2·42	0·0040	2·451	(3)
Iron (cast) .	$11 \cdot 13 \times 10^{-6}$	16×10^6	19,500	9 to 15	0·0062	—	
Iron (wrt.) .	$11 \cdot 9 \times 10^{-6}$	30×10^6	65,000	10 to 11	0·0062	0·695	(3)
Lead . .	$28 \cdot 4 \times 10^{-6}$	$0 \cdot 72 \times 10^6$	1,500 to 3,000	20·8	0·0043	3·858	(2)
Magnesium .	$25 \cdot 9 \times 10^{-6}$	$3 \cdot 5 \times 10^6$	20,000 to 30,000	4·35	0·00381	0·4542	(2)
Mercury .	$59 \cdot 8 \times 10^{-6}$	—	—	94·07	0·0009	3·729	(2)
Nickel . .	$13 \cdot 7 \times 10^{-6}$	25×10^6	40,000 to 85,000	12·3	0·0041	0·730	(3)
Palladium .	$11 \cdot 7 \times 10^{-6}$	$16 \cdot 4 \times 10^6$	—	10·7	0·0037	—	
Platinum .	$9 \cdot 54 \times 10^{-6}$	$24 \cdot 4 \times 10^6$	30,000 to 50,000	10·92	0·0038	1·816	(4)
Silver . .	$18 \cdot 8 \times 10^{-6}$	$11 \cdot 45 \times 10^6$	40,000 to 45,000	1·66	0·0040	4·025	(1)
Steel (wire) .	$10 \cdot 8 \times 10^{-6}$	30×10^6	50,000 to 300,000	17 to 47	0·0016 to 0·0042	0·695	(3)
Tantalum .	—	27×10^6	130,000	14·6	0·0033	1·350	(5)
Tin (cast) .	$21 \cdot 65 \times 10^{-6}$	$3 \cdot 5 \times 10^6$	5,000	13	0·0045	1·109	(4)
Tungsten (wire) .	$4 \cdot 44 \times 10^{-6}$	—	600,000	5	0·0051	3·431	(2)
Zinc (sheet) .	$26 \cdot 3 \times 10^{-6}$	$13 \cdot 4 \times 10^6$	16,000	6 to 6·5	0·0037	1·219	(2)

[British Aluminium Co.]

included with these metals certain others, e.g. gold, silver, palladium, and tantalum, are given for comparison purposes.

The Light Alloys Used in Engineering

With the rapid development of aircraft and automobiles the use of light and strong alloys has become extensive and enabled considerable reductions in the weights of various components to be effected. Of the available alloys employed for these purposes, aluminium and magnesium are the most important constituent or basic metals, and alloys of these in the form of sheets, rods, tubes, forgings, sand and die-castings are now in common use and frequently employed to replace parts hitherto made of steel. Apart from their applications in the aircraft and automobile industries, light alloys have also numerous uses in the various fields of mechanical and electrical engineering.

Whilst it is not possible to refer to the numerous examples which occur, in the different spheres of engineering, of the replacement of steel parts by those made from the lighter alloys, one particular instance may be quoted, namely, in connection with aircraft engines. Of the materials used in the construction of engines prior to 1914 over 90 per cent, by weight, were ferrous, i.e. steels and cast iron. In 1938 an analysis of the existing aircraft engines revealed that only 42 to 48 per cent of the weight was due to the use of alloy steels, whereas from 47 to 53 per cent was due to the use of light non-ferrous alloys and 3 to 5 per cent heavy non-ferrous alloys. From 0·2 to 0·5 per cent of the weight was made up of non-metallic materials, namely, sparking plug insulators, cable and ignition plant insulators.

Other examples of the use of light alloys in place of steel and cast iron are given in the chapters on aluminium and magnesium and their respective alloys.

Weight, Strength, and Stiffness Considerations

In connection with the selection of materials for engineering parts and structures of minimum weight, assuming that the available materials can be fabricated into the required shapes with equal facility, and are not discounted on account of physical properties, such as corrosion, wear, etc., then the choice of the most suitable material involves considerations of the specific gravity, mechanical strength and stiffness.

Thus, for the lightest structure *the ratio of strength to weight* should be a maximum. In this connection the strength is taken as the working stress, e.g. tensile, compressive, torsion or combined, to which the structure is subjected and the weight as represented by the specific gravity or density. Further, the *ratio of the stiffness to weight* should be a maximum so as to give minimum deflection under load or to enable suitable members to be used without the necessity of additional stiffeners.

Additional requirements in the case of metal parts are that the metals should be capable of being machined at high speeds with available machines and tools; fabricated with ease and the minimum of heat-treatment; be weldable by both oxy-acetylene and electric processes without special technique; be available in quantity and at a cost that is not excessive.

An interesting comparison may be made between the strength and weight properties of a typical alloy steel, a wrought aluminium alloy and a wrought magnesium alloy, the properties of which are given in Table 3.

TABLE 3

COMPARISON OF STEEL AND LIGHT ALLOYS

Material	0·1% Proof Stress* Tons per sq. in.	Ultimate Stress Tons per sq. in.	Specific Gravity S.G.	Proof Stress / S.G.	Modulus of Elasticity Lb. per sq. in.
High tensile steel .	50	65	7·85	6·36	29 × 10⁶
Aluminium alloy .	22	28	2·85	7·72	10·5 × 10⁶
Magnesium alloy .	12	17	1·83	6·55	6·5 × 10⁶

* Proof Stress (0·1%), as defined by the B.E.S.A., is that stress at which the stress-strain curve departs by 0·1 per cent of the gauge length from the straight line of proportionality.

These results show that the aluminium and magnesium alloys have a better strength-to-weight ratio than the steel. It should be mentioned, however, that alloy steels having a proof stress of 65 tons per sq. in. are employed in engineering so that such steels would have a higher strength-to-weight ratio than either of the light alloys in question.

In the case of tubular and sheet metal constructions requiring the maximum strength for a given weight, the use of high tensile steels is often limited by the fact that the sections of the members become too thin and are liable to buckle under compression loads. Although special built-up sections of box-like form can be employed, it is generally more satisfactory to use a light alloy which gives a greater thickness of metal for the same strength properties. Other disadvantages of thin alloy steel sections are the difficulties of taking concentrated load effects, the necessity for laminations where tapered sections would be used for light alloys and increased difficulty in obtaining satisfactory riveted joints. In the latter connection a higher efficiency figure is obtained for rivet values in shear against the thicker wall of the light alloy. These considerations are of special importance in connection with aircraft metal constructions.

It is possible to make comparisons between the weight, strength and stiffness of sheet metals of different materials. Thus, if the thickness of the sheet be denoted by t, then the weight for a given size of sheet will be proportional to t, the strength in bending to t^2, and the stiffness in bending to t^3.

If the values for the proof stresses, weights and moduli of elasticity given in Table 3 are employed, the comparative weights, strengths and stiffnesses of sheet metals of thickness t will be as shown in Table 4. It will be observed from the second column that these quantities

are considered for conditions of (1) equal thickness of sheet, (2) equal tensile strength (proof stress), (3) equal stiffness, and (4) equal weight.

TABLE 4
COMPARISON OF WEIGHTS, STRENGTHS, AND STIFFNESSES OF SHEET METALS

Material	Comparison	t	t^2	t^3	Weight	Strength $t^2 \times f$	Stiffness $t^3 \times E$
Steel . .	Equal Thickness	1	1	1	100	100	100
Aluminium alloy		1	1	1	36	44	36
Magnesium alloy		1	1	1	23	24	23
Steel . .	Equal Strength	1	1	1	100	100	100
Aluminium alloy		1·51	2·28	3·44	54·8	100	124
Magnesium alloy		2·04	4·16	8·49	47·5	100	190
Steel . .	Equal Stiffness	1	1	1	100	100	100
Aluminium alloy		1·4	1·96	2·76	51	86·2	100
Magnesium alloy		1·64	2·7	4·46	38	64·8	100
Steel . .	Equal Weight	1	1	1	100	100	100
Aluminium alloy		2·75	7·55	20·8	100	332	750
Magnesium alloy		4·3	18·4	80	100	442	1790

t = thickness, f = proof stress, E = modulus of elasticity.

The results given in Table 4 illustrate several interesting points showing to the advantage of the lighter alloys when used in greater thicknesses than for steel. Thus, for equal strengths, it is necessary to use aluminium alloy plates 51 per cent thicker than steel, but the relative weight is only 54·8 per cent of that of the steel plate; further, the stiffness of this thickness of plate for the aluminium alloy is 24 per cent greater than for steel of equal strength.

The magnesium alloy plate of equal strength is about twice the thickness of the steel plate, is less than one-half the weight and nearly double the stiffness.

For plates of equal stiffness the aluminium and magnesium alloys require to be 40 and 64 per cent thicker respectively; they weigh only 51 and 38 per cent of the steel plate, but have only 86·2 and 64·8 per cent of the tensile or bending strength.

When the comparison is made on the basis of equal weights it will be observed that the strengths of the aluminium and magnesium alloys are 3·32 and 4·42 as great as for steel, and the stiffness 7·5 and 17·9 times as great respectively.

An interesting comparison of the strength and rigidity of beams made of steel and R.R. 56 aluminium alloy is shown in Fig. 1.*

* Bureau of Information on Nickel.

The following are particulars of the two metals in question—

TABLE 5

COMPARATIVE PROPERTIES OF STEEL AND R.R. 56 ALLOY

Metal	Specific Gravity	Tensile Strength (Tons per sq. in.)	Young's Modulus × 10⁶ lb. per sq. in.
Steel	7·9	35	30
R.R.56 alloy, heat-treated and aged . . .	2·8	29	10·5

The diagrams and data given in Fig. 1 show that for equal bending strength and deflection the R.R. 56 alloy beams are much lighter than the steel ones; further, the lower elastic modulus value of the former alloy is compensated for in regard to the deflection by suitable alteration of design of the section.
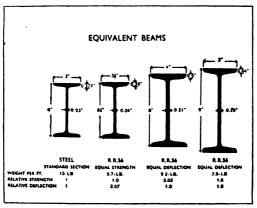
FIG. 1. COMPARISON OF EQUIVALENT BEAMS IN STEEL AND R.R. 56 ALLOY

Another useful method of comparison is given in Fig. 2 for beams of the same two metals.

In this connection the letter a represents one side of the square. Thus, for beams of equal stiffness it is seen that the weight of R.R.56 is 60 per cent of that of steel, while the strength is 265 per cent.

For beams of equal weight the stiffness of R.R.56 is 278 per cent of that of steel, and its strength 388 per cent.

The letter d equals depth of beams.

Thus, for equal stiffness, the strength of the R.R.56 beam is 164 per cent of that of steel, whilst its weight is 50 per cent.

For beams of equal weight the strength is 660 per cent of that of steel, whilst the stiffness is 790 per cent.

			Steel.	R.R.56.	R.R.56.	R.R.56.
a	...	...	1	1	1·3	1·67
Weight	...	...	100	35·4	60	100
Strength	...	...	100	83	265	388
Stiffness	...	...	100	35·	100	278

Constant width, conditions as in, for example, sheet.

			Steel.	R.R.56.	R.R.56.	R.R.56.
d	...	...	1	1	1·4	2·82
Weight	...	...	100	35·4	50	100
Strength	...	...	100	83	164	660
Stiffness	...	...	100	35	100	790

FIG. 2. ANOTHER METHOD OF COMPARISON OF STEEL AND R.R.56 ALLOY BEAMS

Aircraft Structure Considerations

In addition to the information previously given it may be mentioned that in regard to the selection of the most suitable materials light alloys have replaced steel for a large number of parts. In one typical example, namely, that of the metal stressed-skin covering, steel sheet does not give the necessary degree of stiffness and light alloys are invariably used for the purpose. Another application is for the cylinders of undercarriage compression struts for which the light alloys give a greater wall thickness for a given weight, namely, from 3 to $4\frac{1}{2}$ times that of 50-ton (proof stress) steel and therefore greater strength in compression or buckling.

For many purposes, however, where parts are subject to fatigue or impact effects, steel is superior for solid members, but for thin sections under buckling loads the lighter alloys are preferable.

An interesting comparison of the relative merits of steels and light alloys for aircraft structures* is given in Table 6, for the various applications mentioned.

* *The Bristol Review*.

TABLE 6

COMPARISON OF STEEL AND LIGHT ALLOY FOR SPECIFIED USES

Details	Steel	Light Alloy
Flanges (Wing Spars)	Flanges formed from strip into special shapes and laminations to give the required tapered effect for constant strength against loading from root to tip.	Flanges formed from extruded sections in simple shapes, machined towards the tip for taper.
Webs	Webs corrugated for stability in thin gauges and having numerous vertical stiffeners.	Webs of flat sheet with vertical stiffeners.
End fittings	End fittings presenting difficulties in certain cases, where shape has to conform to the formed sections of the flanges.	Steel end fittings may be used, but they will be of relatively simple form when picking up the extruded flange sections.
Formers and stringers on wings or fuselages	Can be readily formed into suitable shape, but in order to keep down weight and remain stable in thin gauges, the I of the section would be relatively small.	Can be readily formed into shape. The overall size compared with steel would be greater (due to wall thickness ratio of 3 : 1 relative to steel), consequently giving a better figure for the I.
Ribs for all planes	These would probably have to be built up from formed sections to keep within the weight allowance. If made from sheet, a big percentage of the material would be removed in the form of special shaped lightening holes to retain stability over the plain areas.	Made from sheet with circular lightening holes, flanged to give stability.
Covering: planes and fuselage	Special forming operations would be required on the sheet to retain stability over the unsupported areas. This would lead to great difficulties in assembling and joining operations in the light gauges, which would necessarily have to be used to keep the weight figure within that allowed.	Can be safely used in the flat down to a thickness of 24 S.W.G. without presenting any real difficulty in breaking up the free areas to retain stability.
Engine mounting and undercarriage parts subjected to high-frequency vibrations and alternating load	Steel fittings having a superior fatigue range possess the qualities necessary for this group, and, owing to their high load-carrying capacity, give a compact detail with minimum scantling sizes. Forged fittings up to 65 tons per sq. in. are available for this group.	Fittings made under this group will only be found entirely suitable in certain cases. They are not generally considered so good as those under the steel heading.

In connection with the use of light alloys for aircraft and similar applications where wall and section thicknesses must not be less than certain minimum values under given strength or stiffness conditions, the use of extruded light alloys of various sections is recommended; a typical selection of such sections made by Reynolds Tube Co., Ltd., is given in Fig. 3.

With regard to the use of the strong light aluminium alloys in

aircraft construction, apart from the use of castings, the forged and heat-treated alloys are employed for most of the stress-bearing members of the airframe in the forms of extruded sections or large tubes; some of these members are tapered in gauge. The use of extruded sections is now general throughout the framework of modern aircraft.
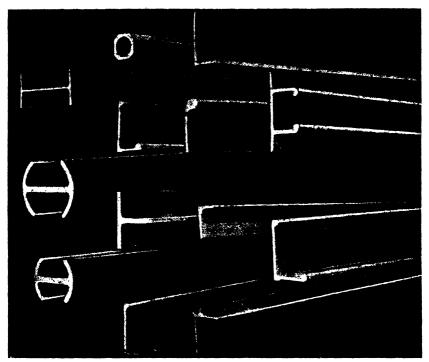
FIG. 3. A SELECTION OF EXTRUDED SECTIONS IN LIGHT ALLOY

Some typical examples and applications of these sections are given in Fig. 4* for alloys of the duralumin, R.R. and super-duralumin classes. Further applications of light alloy components are shown in Figs. 5 and 6.

The coverings of modern all-metal aircraft are usually of aluminium alloy, clad with pure aluminium, in order to withstand atmospheric corrosion effects.

Although the stronger aluminium alloys are used for stress-bearing

* "Materials of Aircraft Construction," H. J. Gough, *Journ. Roy. Aeron. Soc.*, 26th May, 1938.

members, the lighter magnesium alloys are employed for fittings and parts of secondary importance, where weight saving can be effected. In general, the tendency is to avoid built-up alloy structures as far as possible and to substitute castings or wrought alloys in the forged or extruded forms for these. Concerning the use of sheet materials, about

COMPOSITE SPAR BOOM SECTION.

FUSELAGE STRINGER.

STRINGERS FOR MONOCOQUE FUSELAGE.

MAIN SPAR FLANGE AND ATTACHMENT.   WING SPAR FLANGE.

TYPICAL EXAMPLES   TYPICAL APPLICATIONS
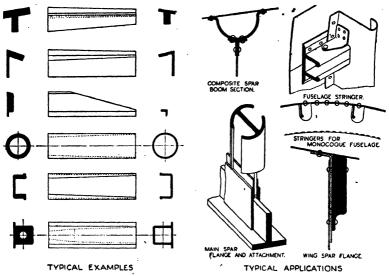
FIG. 4. EXTRUDED LIGHT ALLOY SECTIONS AND SOME TYPICAL APPLICATIONS

50 per cent of the alloy parts used in modern aircraft are of plain duralumin, about 40 per cent of "clad" alloys and the rest in one of the stronger alloys. About 60 to 70 per cent of the extrusions and parts machined from bars are of plain duralumin and the remainder of stronger alloys such as R.R.56. About 80 per cent of the tubes are of plain duralumin and the remainder of stronger light alloys.

Light alloys, with ultimate stress values up to 28 tons per sq. in., are available, and parts made from such alloys include aircraft engine cylinder heads, pistons, variable-pitch airscrew blades, operating levers, retractable undercarriage components, brackets, supercharger parts, covers, cowlings, main bearing caps of engines, engine bearers, etc.

The use of these alloys, however, involves special attention to protection against corrosion, local wear effects and the effect of temperature upon the strength values of the alloys, etc.

The magnesium group of alloys, in particular, is readily corrodible

and must therefore be protected by special surface treatments when used under normal service conditions.

Many of the aluminium alloys, of which duralumin is a typical example, require a particular heat-treatment in order to develop their
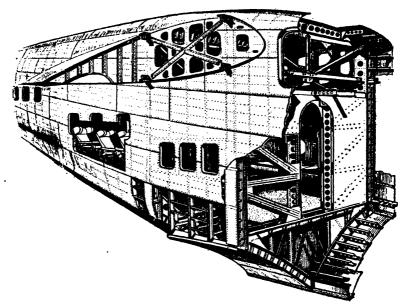
FIG. 5. ILLUSTRATING USE OF LIGHT ALLOY MEMBERS FOR THE HULL AND WINGS OF LARGE FLYING BOAT (GOUGH)
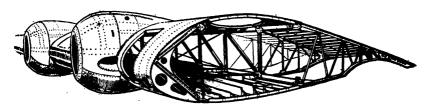
FIG. 6. WING CONSTRUCTION OF LARGE FLYING BOAT

full strength and hardness qualities. Some of these alloys also undergo a gradual hardening process after annealing; this is termed "ageing," so that it is necessary for cold-working and riveting purposes to use these parts within a relatively short period after softening has been effected.

Temperature Effects on Light Alloys

In connection with the application of light alloys to internal combustion engines for components which are subject to normal working temperatures appreciably above atmospheric values, special consideration must be given to the effects of these temperatures upon the strength and hardness properties of the metals. Although at ordinary air temperatures some of the available alloys are superior to steel in regard to their strength-to-weight ratios and have much better thermal conduction properties, the correct basis of comparison should always be made under actual working temperature conditions; in this respect most light alloys show a notable falling off in strength and hardness values with temperature increase. There are, however, certain of these alloys which still retain sufficient strength at normal engine working temperatures to justify completely their substitution for steels for parts such as pistons and cylinder heads.

The strength of a light alloy at elevated temperatures involves two principal considerations, namely (1) the effect of the working temperature upon the mechanical properties, and (2) the effect of prolonged exposure to high working temperatures upon the mechanical properties after cooling down to air temperatures. The results of investigations show that the effects of exposing different light alloys to high temperatures are not always regular. Thus, the alloys which derive their strength properties from the application of cold work, e.g. rolling or extrusion, will be permanently softened by exposure to high temperature. Other alloys, which age-harden at temperatures of about the room air temperatures, are unaffected at high temperatures, unless these reach or exceed the annealing temperatures, when softening will occur. Other alloys will become harder, but more brittle, when exposed to high temperatures below the annealing temperature.

In regard to the order of the temperatures experienced in the case of air-cooled engines used for aircraft these seldom exceed about 375° C. in the case of light alloy cylinder heads and 350° C. for the highest temperature of the piston crown. Fig. 7 illustrates the usual

FIG. 7. TEMPERATURES OF ALUMINIUM ALLOY CYLINDER HEAD AND PISTON

temperature values for a radial air-cooled engine. The hot metals surrounding the combustion chamber space are, in addition, exposed to rapidly varying pressure effects due to the working cycles; the maximum pressure values generally lie between about 600 and 700 lb. per sq. in.

The aluminium light alloys used for petrol engine cylinders and
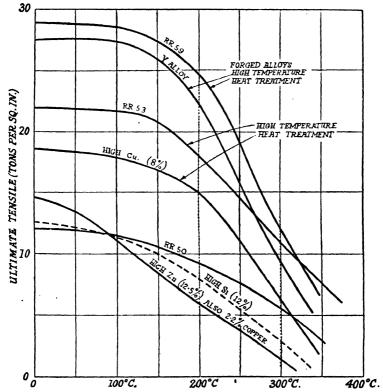
FIG. 8. CURVES SHOWING THE STRENGTH AT ELEVATED TEMPERATURES OF VARIOUS ALUMINIUM ALLOYS AFTER BEING MAINTAINED FOR 30 MINS. AT THE TEMPERATURES INDICATED

pistons have included copper, zinc and silicon content metals, but the more recent materials of this class are Hiduminium R.R.50, R.R.53, and R.R.59 and Y-alloy. The two latter alloys are employed as forgings and the cylinder heads machined from them. Sand-cast R.R.50 and R.R.53 alloys are also used for intricate shapes.

The strengths of these alloys at various temperatures up to about 350° C. are shown graphically in Fig. 8. The general trend of the Hiduminium and Y-alloy curves indicates that there is practically

no diminution in tensile strength for temperatures up to about 100° C., but for higher values the strength falls rapidly, until at 300° C. the values lie between about one-third and one-half of the normal air temperature ones.

The wrought high-strength magnesium alloys used for certain parts of aircraft engines, such as the crankcases and cylinder head covers, also show an appreciable diminution of strength with temperature increase, the results being more accentuated, as a rule, than in the case of aluminium alloys. Some comparative results for the magnesium alloy known as Elektron and three other high strength aluminium alloys are given in Table 7. It will be seen from these

TABLE 7

STRENGTHS OF LIGHT ALLOYS AT ELEVATED TEMPERATURES

Temperature °C. of Test	Ultimate Tensile Stress in tons per sq. in.			
	Elektron AZ.855	Duralumin	Y-Alloy	R.R.56
20	20·0	26·5	25·0	27·0
100	16·5	25·5	23·5	24·0
150	13·7	22·5	22·5	22·5
200	12·0	20·0	21·5	21·0
250	6·0	18·5	21·0	20·5
300	—	13·0	16·5	15·0
350	—	8·0	13·0	10·0

values that at 250° C. the magnesium alloy has only 30 per cent of its normal air temperature strength, whereas duralumin, Y-alloy and R.R.56 have 70, 84 and 76 per cent respectively · these results emphasize clearly the superiority of the aluminium alloys for petrol engine cylinders (with steel liners), cylinder heads and pistons. Mention should here be made of certain special magnesium alloys having rather higher strengths at elevated temperatures than the example given in Table 7. Thus an alloy containing 10 per cent cerium, 1·5 per cent cobalt, 1·5 per cent manganese and the rest magnesium has a tensile strength of 18·6 tons per sq. in. at 20° C., 13·2 tons per sq. in. at 200° C. and 7·4 tons per sq. in. at 300° C.

The cast magnesium alloys used for aircraft engines show a somewhat similar rate of decrease of strength with temperature increase, but have lower initial strength values at air temperatures. Thus, Elektron AZG and A.8 sand-cast alloys have yield points of 6 to 7 tons per sq. in. and tensile strengths of 10 to 12 tons per sq. in.* with 5 to 3 per cent elongation and 45 to 55 Brinell hardness values.

* Solution treated alloys give maximum values of 15 to 20 tons per sq. in.

Concerning the *effect of temperature upon the hardness* oi light aluminium alloys, although there is generally little alteration for temperatures up to 100° C., above this value the hardness falls progressively until at 400° C. it is from 50 to 63 per cent of the normal air value. Table 8 shows the results of hardness tests* on typical wrought light alloys after reheating to elevated temperatures, after complete heat-treatment.

TABLE 8
BRINELL HARDNESSES OF LIGHT WROUGHT ALLOYS AT ELEVATED TEMPERATURES

Temperature °C.	Duralumin	Y-Alloy	R.R.56 Alloy
20	106·5	98·0	130
100	106·5	98·0	130
150	95·0	98·0	130
200	90·0	98·0	125
250	85·0	98·0	110
300	77·0	85·0	82
400	61·5	62·5	62

It will be seen that for temperatures up to about 250° C. the Y-alloy maintains its hardness better than the other alloys.

The effect of prolonged exposure to high temperatures upon the hardness of light alloys of the wrought class is illustrated by the results given in Table 9 for specimens exposed at 200° C. for a period of 13 weeks. The alloys in question were fully heat-treated before testing.

TABLE 9
EFFECT UPON HARDNESS OF PROLONGED EXPOSURE AT 200° C.

Material	Brinell Hardness Number	
	Before Exposure	After Exposure
Age-hardened duralumin . . .	114·0	60·5
Age-hardened Y-alloy	96·3	69·1
Artificially-aged R.R.56 alloy . .	130·0	58·6

The superiority of the Y-alloy to the effects of prolonged exposure at 200° C. is clearly indicated by the results in Table 9.

* "Strong Light Alloys of To-day," L. Aitchison, *Proc. Inst. Autom. Engrs.*, March, 1933.

Equilibrium Diagrams of Alloys

In subsequent considerations of various alloys in this volume, their constitutions are referred to in many instances, so that it may be of interest to give a brief account of this subject for the benefit of those readers who are not conversant with it.

When two different metals are melted and mixed together an alloy is usually produced consisting of a solution of one of these metals in
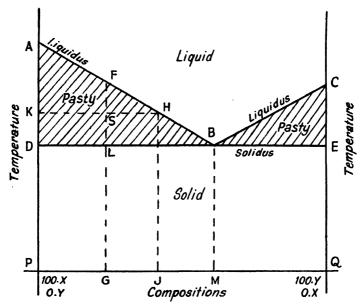
FIG. 9. SIMPLE EQUILIBRIUM DIAGRAM FOR TWO METALS X AND Y

the other. If the metals and compositions are suitably selected, when the molten mass is cooled down it forms a uniform and homogeneous solid which behaves as a metal but with different properties from either of the two constituents. This solid metal is known as a *solid solution*. In general, in the case of alloys of two metals, the solid solution usually has superior properties to those of the constituent metals. Thus, the commonly used brasses (copper-zinc alloys) and bronzes (copper-tin) have much better mechanical properties than any of the individual metals concerned.

Solid solutions do not, however, occur except under special circumstances, the usual process being that of the formation of an intermetallic compound of definite composition. This compound may, however, dissolve in an excess of one of the metals and thus form

another kind of solid solution. Usually, the intermetallic compound is of a hard and brittle nature and has no practical application.

It will be seen that an alloy does not usually consist of a simple solid solution but contains two or three substances or *phases*; it is the nature and proportion of the latter that determine the properties of the alloy· The phase relationships in alloys are more conveniently studied from the *equilibrium* (or *constitutional*) *diagrams*, namely, diagrams of temperature and composition, showing the melting and solidifying points of the various alloys.

Fig. 9 illustrates a typical equilibrium diagram for two metals designated by the letters X and Y. These metals are mixed in various proportions between 100 per cent X and 0 per cent Y (as indicated at P) and 100 per cent Y and 0 per cent X (as at Q). The melting points of all the alloys between P and Q are shown by the lines AB and BC, known as the *liquidus line*. All points on the equilibrium diagram above the line ABC correspond to the liquid state of the alloys.

The areas ABD and CBE correspond to the partly solidified alloys or "pasty" condition.

The alloy of X and Y having the lowest melting point corresponds to that of the point B. This alloy when cooled from the liquid condition above B does not pass through any pasty condition but solidifies suddenly. It is known as the *eutectic* of X and Y and is composed of X and Y in the proportions of BE to DB.

The behaviour of any alloy, such as that represented by the point G (corresponding to GQ of X and PG of Y), when cooled from the liquid condition may be studied by drawing the ordinate FLG. When cooled from the liquid to the point F on the liquidus curve, crystals of X commence to deposit. As the temperature falls gradually towards that of the point L, more and more crystals of X are deposited.

The solution in which these crystals form consists of the pure metal Y, and it follows that as the temperature falls towards L, this solution must become richer and richer in the metal Y, since more and more of the crystals of metal X are being deposited. At any intermediate temperature S, the proportion of the liquid Y is represented by the abscissa KSH. As cooling proceeds this composition point H moves towards B until, when the temperature reaches the *solidus line DLBE*, the liquid has the composition denoted by the eutectic point B.

If the point F had been selected on the line BC, then the cooling process would have consisted in the deposition of crystals of the pure metal Y in a liquid solution of X.

Usually, the equilibrium diagrams of commercial alloys are more complex than the simple eutectic type shown in Fig. 9, as most of the alloys undergo more than one transformation in cooling from the liquid to solid states.

An example of such a diagram,* given in Fig. 10, will serve to indicate the general changes that occur in such instances.

In this diagram the line *HFI* is the liquidus and *GFE* the solidus for the metals denoted by the letters *A* and *B* respectively. The areas *HGF* and *FEI* represent the "pasty" state. The area *ACGH* indicates
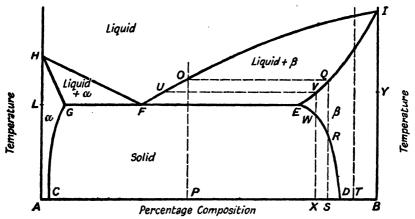
FIG. 10. GENERAL TYPE OF EQUILIBRIUM DIAGRAM FOR A SOLID SOLUTION

that the metal *B* is soluble to some extent in *A*; thus at normal air temperature the metal *B* is soluble in *A* by the amount represented by *AC*. Similarly *A* is soluble in *B* by the amount *DB* at normal temperature. When the alloy is at the temperature *L* corresponding to *GFE*, namely, the eutectic one, the solubilities increase by the amounts represented by the horizontal distances of *G* and *E* from the lines *AH* and *BI*, respectively. The alloy of composition *F* is the eutectic, but consists not of a mixture of *A* and *B* but of the solid solutions represented by α and β. At the temperature *L* the first solid eutectic consists of α solution of composition *G* and β solution of composition *E*.

In the case of an alloy of composition *P*, cooled from the liquid state above *O*, the first solid to separate out at *O* consists of α solid solution of composition *Q*. The liquid, as the solid portion separates out with falling temperature, becomes richer in the metal *A*, and the

* "Copper and Its Alloys," F. A. Fox, *Machinery*, 14th April, 1938.

composition moves towards the point F. At the temperature Y the solid deposited consists of β solution as given by V and the composition of the liquid is represented by U; this composition, with falling temperature, moves along OF and that of the solid along QE. At the temperature L, the composition of the liquid is F and this solidifies as eutectic. The alloy then consists of primary β solution and eutectic. With further diminution of temperature the β solid solution cannot retain in solution all of the A metal it contains and commences to break down into a mixture of α solid solution and β solid solution containing less of A; this change is denoted by the crossing of the line ED at points such as R and W. When the alloy is at air temperature it consists of β solid solution of composition up to D and eutectic of composition F.

The alloy of composition T will solidify without forming a eutectic and will consist entirely of β solid solution.

CHAPTER II

ALUMINIUM

COMMERCIAL aluminium is obtained chiefly from *Bauxite*, an impure hydrated aluminium oxide, and *Kaolin*, or *China Clay*, a double silicate of aluminium. Other natural ores include *Corundum* (aluminium oxide) and the *Fluoride*—a double fluoride of aluminium and sodium.

The metal is usually extracted from bauxite by an electrolytic extraction process employing the electric arc type of furnace; the Héroult electric furnace is a typical example of the latter.

Aluminium is a white lustrous metal having a specific gravity of 2·703 to 2·710, i.e. about one-third the weight of iron, and possessing excellent thermal and heat conductivities.' It is also noted for its resistance to corrosion under atmospheric conditions. The physical properties of pure aluminium are given in Table 10.

TABLE 10

PHYSICAL PROPERTIES OF PURE ALUMINIUM

Property	Value	Authority
Atomic Weight (Oxygen = 16) . . .	26·97	Int. Atomic Wt. Comm., 1929.
Spec. Ht., 20°–400° C. (av.) cals. . .	0·24	Int. Crit. Tables Formula.
Spec. Thermal Conductivity in cals. per cm. cub⌐ per degree C. per sec., at 0° C. . .	0·502	Bailey, Proc. Roy. Soc. A., 134, 57–76, 1931.
Approx. Relative Heat Conductivity (Silver = 100%)	51·8	
Melting Point (99·97% pure) °Cent. . .	659·8	} Edwards, J., American
„ „ (99·66% pure) °Cent. . .	658·7	} Electrochem. Soc., 1925.
Boiling Point, °Cent.	1800	Greenwood, Proc. Royal Soc. 82, 1909.
Latent Ht. of Fusion, cals. per gm. . .	92·4	
Total Ht. referred to 20° C., calories per gm. 400° C.	88	} Awbery & Griffiths, Proc.
„ „ 600° C.	146	} Phys. Soc., Lond. Vol. 38,
„ „ 700° C.	267	} pt. 5, Aug. 15, 1926.
Vapour Pressure at 658·7° C., mm. of Mercury	1·0 × 10⁻⁴⁰	Richards, Jour. Franklin Inst., Vol. 187, 1919.
Heat of Combustion to Al₂O₃ per gm. mol., cals.	383,900	A.S.S.T. Handbook.
Coeff. of Linear Expansion /°C. H.D. Wire, 0°–30° C.	23 × 10⁻⁶	B.S. Spec. 215.
Rolled metal (normal purity),	23 × 10⁻⁶	
Average value, 20°–100° C. . . .	24 × 10⁻⁶	} Based on Hidnert. U.S.
„ „ 20°–300° C. . . .	26·7 × 10⁻⁶	} Bureau of Standards Paper
„ „ 20°–600° C. . . .	28·6 × 10⁻⁶	} No. 497.
Specific Gravity— H.D. Wire (electrical conductors) . .	2·703	B.S.S. No. 215, 1934.
Rolled sheet (normal purity) . . .	2·71	British Aluminium Co. Ltd.
Molten (99·75% pure), 658·7° C. . .	2·382	} Edwards & Moorman, Chem.
„ „ „ 1100° C. . .	2·262	} Met. Eng., Vol. 24, pp. 61–64, 1921.
Wt. of 1 cub. ft. of Aluminium (normal purity), lb.	169·18	Calculated from Specific Gravity.

TABLE 11

MECHANICAL PROPERTIES OF ALUMINIUM

Property	Value	Authority
Modulus of Elasticity, lb./sq. in. . . .	$9 \cdot 9 \times 10^6$	B.S.S. No. 215, 1934.
Torsion Modulus, lb./sq. in.	$3 \cdot 87 \times 10^6$	Koch & Dannecker, Ann. d. Phys., 1915.
Poisson's Ratio	$0 \cdot 36$	Bureau of Standards, Circ. No. 76, 1919.
Tensile Strength of Sheet—		
Annealed, tons/sq. in. . . .	$5-6\frac{1}{4}$	B.S.S. No. 2L17, 1922.
Half-Hard. tons/sq. in. . . .	$7-8\frac{1}{4}$	B.S.S. No. 2L16, 1922.
Hard, tons/sq. in.	9 (min.)	B.S.S. No. 2L4, 1922.
Percentage Elongation in 2 in.—		
Pure Castings, Sand	20–30	British Aluminium Co., Ltd.
,, ,, Chill . . .	30–40	,, ,, ,,
Pure Sheet, Annealed . . .	12–40	,, ,, ,,
,, ,, Half-Hard . . .	5–12	,, ,, ,,
,, ,, Hard . . .	2–8	,, ,, ,,
H.D. Wire	4–7	,, ,, ,,
Scleroscope Hardness (mag. ham.)—		
Annealed or Cast	$5-5\frac{1}{2}$	,, ,, ,,
Cold rolled ($\cdot128''-\cdot020''$) . .	15–22	,, ,, ,,
Brinell Hardness, 1 mm./5 kgm.—		
Cast	20–28	,, ,, ,,
Annealed Sheet	19–23	,, ,, ,,
Hard Sheet	38–45	,, ,, ,,

TABLE 12

ELECTRICAL PROPERTIES OF ALUMINIUM

Property	Value	Authority
Max. Specific Res. for } microhms/cm. cube.	2·8735	B.A. Co. Guaranteed maximum
H.D. Wire at 20° C. . } microhms/in. cube .	1·1313	
Standard Specific Res. for } microhms/cm.cube .	2·845	B.S.S. No. 215, 1934. ,,
H.D. Wire at 20° C. . } microhms/in. cube .	1·1199	,, ,,
Coefficient of increase of res. with temp. } °C. .	0·00407	,, ,,
for H.D. wire at 15·6° C. (60° F.) . } °F. .	0·00226	,, ,,
Electrochem. equivalent, grs. per coulomb .	0·00009316	Calculated from stand. val. for silver.
Electrolytic solution potential against a normal hydrogen electrode (in normal aluminium sulphate) volts	1·3	Bureau of Standards Circ. 346.
Thermo-electromotive force against pure platinum for 99·97% Al. at 100° C., millivolts .	+ ·416	,, ,, ,, ,,
Magnetic Susceptibility at 18° C. . . .	$0 \cdot 63 \times 10^{-6}$	I.C.T., Vol. VI, p. 354.

Microscopic Structure. Aluminium and its softer alloys are not easy subjects to prepare for microscopic examination, owing to their softness and readiness to scratch and tarnish; the hydrated oxide which forms is difficult to remove without affecting the etched surface. The harder alloys are much easier to prepare for examination.

Iron occurs in aluminium as $FeAl_3$, which is almost insoluble in

solid aluminium, and it is known that no sample of aluminium is absolutely free from this compound.

The presence of this iron compound is shown in unetched specimens as a light coloured constituent, with smaller and darker pieces of silicon (another impurity) em-bedded in a matrix of aluminium.

The structure of aluminium may be examined by treating the polished surface successively with caustic soda (to combine with the metal) and nitric acid (to remove this compound). Alternatively, caustic soda and aqueous hydrofluoric acid may be used.

FIG. 11. ALUMINIUM SHEET, ROLLED
(× 150)

FIG. 12. ALUMINIUM SHEET, ANNEALED
(× 150)

Figs. 11 and 12 show the structure of ordinary sheet aluminium, in the rolled and annealed states respectively.

The effect of rolling is to give a distinct grain effect in the direction of rolling, which annealing effectively removes.

The structure of pure aluminium is minutely granular in appearance as seen in etched specimens.

Commercial Aluminium

The commercial grades of aluminium used for rolling into sheets for domestic, industrial and chemical purposes are about 99·0 per cent pure, whilst that employed for electrical conductors is 99·5 per cent pure. The impurities usually found in such commercial aluminiums are iron and silicon; traces of copper, sodium and zinc are sometimes present.

Aluminium sheet is supplied normally with a bright finish but if desired the satin and frosted finishes are supplied. Another kind of finish, known as the "Anodized Quality" is used when sheets are to be given a decorative anodic or protective oxide coating.

Commercial sheets and strips are available in five different tempers, known as Soft, Quarter-hard, Half-hard, Three-quarters Hard and Hard. Of these the first, third and fifth correspond to British Standard Specifications 2L.17, 2L.16 and 2L.4 respectively. Particulars of these sheets and strip are given in Table 13. Regarding the various tempers, these can be obtained by various amounts of cold rolling under suitable pressures.

Commercial aluminium is supplied in the form of strip, sheet, circles, tubes, matting (for footboards and steps), expanded wire sheets, pipe fittings, wood screws, rivets, rod, wire, various bar sections, foil, powder, etc. It is also supplied in plain and notched bar ingots for casting purposes.

Aluminium Properties and Applications

Commercial aluminium as distinct from the alloys of this metal has a wide variety of uses. Some of its more important properties and applications are given in the following brief notes.

Corrosion-Resistance. Aluminium is unaffected by ordinary atmospheric influences but is corroded in sea-water. It is soluble in solutions of caustic alkalis and in hydrochloric acid. Ordinary washing soda (sodium carbonate) attacks aluminium; nitric, sulphuric, and hydrofluoric acids also slowly dissolve it.

When there is any excess of silicon present in the metal it does not withstand atmospheric corrosive actions.

Annealing. Aluminium sheet which has been hardened by cold working, such as hammering or rolling, can be annealed by heating it to about 350° C. (662° F.) and afterwards cooling in air or water. The period of heating need only be for a few minutes. As a rough guide to the correct temperature of heating for annealing, the surface may be rubbed, during the heating process, with a dry matchstick from time to time, the heating being stopped when the wood begins to char.

TABLE 13

PROPERTIES OF PURE ALUMINIUM SHEET AND STRIP

Temper	Tensile Strength Tons per sq. in.	0·1% Proof Stress Tons per sq. in.		Elongation % on 2 in.		Bend Test	Brinell Hardness	
	Range	Minimum	Average	Minimum	Average		Minimum	Average
Soft . .	5–6·5	—	1·3	33–18*	45–30	Flat bend	20	22
Quarter-hard .	6–7·5	4·2	5·6	10–4*	20–6	Flat bend	24	31
Half-hard .	7–8·5	5·5	6·6	8–3*	14–4	180° bend round radius of $\frac{T}{2}$	29	35
Three-quarters Hard .	8·25–9·75	6·7	7·4	6–2	11–4	ditto	34	38
Hard . .	9·25 (min.)	7·5	7·5	5–2	10–3	180° bend round radius of T	38	41

British Aluminium Co.

* Upper values correspond to 10 S.W.G. sheets and lower ones to 30 S.W.G.
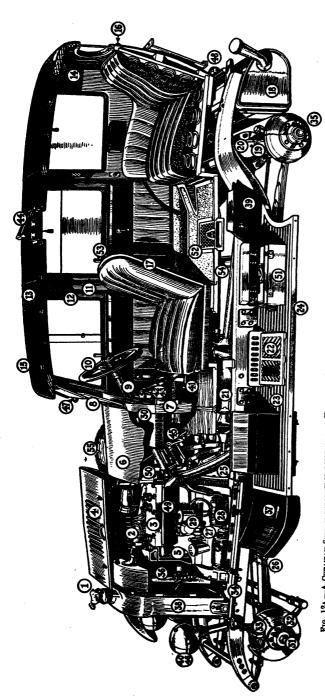
FIG. 12A.—A CUTAWAY SKETCH INDICATING SOME OF THE ECONOMIC APPLICATIONS OF ALUMINIUM AND ITS ALLOYS IN MODERN CAR CONSTRUCTION.

1. Mascot
2. Water circulation system
3. Cylinder block
4. Bonnet
5. Piston and connecting rods
6. Scuttle dash
7. Dashboard
8. Windscreen frame
9. Steering column casing
10. Steering wheel spider
11. Doorplate
12. Window frame

13. Panelling, top, rear, and sides
14. Interior lamp
15. Guttering
16. Moulding
17. Seat frames
18. Petrol tank
19. Axle casing
20. Differential casing
21. Gear-box
22. Scraper and kickplate
23. Matting

24. Step edging
25. Clutch housing
26. Sump
27. Crankcase
28. Magneto parts
29. Carburettor
30. Wire armouring
31. Hub cap
32. Brake drum
33. Brake shoes
34. Bonnet board

35. Wheel discs
36. Fan
37. Wing
38. Radiator hood
39. Valance
40. Head and side lamps
41. Gear lever knob and gate
42. Ashtray
43. Instrument cases
44. Roof ventilator
45. Clutch pedal

46. Lamp reflectors
47. Parking lights
48. Rear lamps
49. Exhaust manifold
50. Dash (between engine and body)
51. Lunch basket
52. Foot warmer (heated from exhaust)
53. Door handles
54. Frame cross-bracing member
55. Spare wheel carrier bracket

27

The annealing of aluminium wire for electrical purposes requires more care, since the aim is to obtain a high electrical conductivity by obtaining the correct structure. For high conductivity a long exposure at a lower temperature, namely, 250° to 300° C., appears to give the best results. In passing, it may be remarked that aluminium alloys require a higher annealing temperature, from about 350° to 400° C.

Melting. Since aluminium oxidizes readily at the higher temperatures it is advisable to use a controllable temperature and a reducing atmosphere. Care must be exercised to prevent overheating of the metal so that thermostatic temperature control is desirable. Aluminium can be melted in ordinary plumbago crucibles, but the modern plumbago variety is a specialized product which has been vitrified by heat-treatment to obviate moisture action; further, the surfaces are rendered impervious to penetration by furnace gases by suitable glaze treatment. Iron pots can also be used if they are suitably protected to avoid pick-up of the metal. This protection can be effected by coating the inside with a wash consisting of 2 lb. of whiting, 1¼ oz. of sodium silicate and 1 gallon of water; an improvement is given to this protective coating if the surface of the iron is first brushed over with a mixture of one part of graphite to two parts of water.

Iron pots have much better heat conduction properties than plumbago ones, and are therefore more economical in heating fuel consumption.

Deoxidizing Properties. Aluminium is used as a deoxidizer for irons and steels and for maintaining large melts of metal in the fluid condition; this effect is due to the reaction caused by the aluminium on the iron or steel. Thus, if aluminium is added to the molten metal it combines with the oxygen and other gases absorbed by the metal from the furnace products and the resultant compound rises to the top of the metal in the form of slag, when it can readily be skimmed off. In this way the formation of blow-holes and similar gaseous inclusions can be avoided. Usually, about 10 oz. of aluminium will deoxidize one ton of steel or iron, satisfactorily.

Electrochemical Property. Aluminium is electropositive to most other metals, e.g. iron, chromium, zinc, copper, nickel, tin, lead, etc. Care is necessary, therefore, to prevent it from coming into metallic contact with other metals, under conditions where moisture is present, in order to avoid electrolytic action, i.e. corrosion.

Electrical Conductivity. If the electrical conductivity of silver—which is the best conducting metal—is taken as 100, then the corresponding conductivities of silver, copper and aluminium are as 100 : 96 : 58·5. Although copper is still widely used as an electrical

conductor, chiefly on account of its better conductivity and ease of jointing, aluminium possesses the marked advantage of low weight as compared with the former metal. As the density of copper is about three times that of aluminium, a copper cable will weigh about twice that of an aluminium one of equal conductance. For this reason large cables, such as those used for transmission lines, e.g. the British Grid System, are now made with aluminium stranded wire conductors. In order to obtain the required tensile strength properties it is generally necessary to reinforce the aluminium wires by employing a stranded
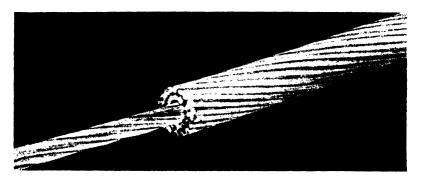
Fig. 13. Section of Aluminium Steel-cored Cable, showing Outer Covering of Aluminium Cable enclosing the Steel
(*Northern Aluminium Co.*)

steel cable core, upon which the former are wound. The complete cable thus made has only 80 per cent of the weight of the equivalent copper one and it is actually much stronger than the latter, namely, about 50 per cent. Aluminium used for electrical purposes is usually protected against corrosion by giving it a thin oxide coating either chemically or electrolytically—as by the anodic treatment method.

Heat Conductivity. The relative heat conductivities of copper, aluminium and iron (or steel) are as 100, 56·6 and 18, respectively. For equal cross-sections of uniform conductor, or equal weights, aluminium will conduct a greater amount of heat than the other metals or, for a given heat transmission, aluminium is the lightest metal to employ. The thermal properties of aluminium alloys are very similar to those of the pure metal and for this reason heat conducting components of petrol engines, e.g. cylinders, cylinder heads and pistons, are now made of these alloys, thus enabling weight to be saved and at the same time allowing greater power output per unit cylinder volume, on account of the higher compression ratios possible.

Aluminium Wire

Aluminium, owing to its great ductility, can be drawn out into fine wires, or beaten into thin leaves. The tensile strength of wire of 0·128 in. diameter is 11 to 12 tons per sq. in., with an elongation in 48 in. of 0·30 to 1·02 per cent and a reduction of area of from 75·0 to 83 per cent.

The tensile strength of commercial wire varies from 6·25 to 14·8 tons per sq. in., according to the diameter and amount of drawing.
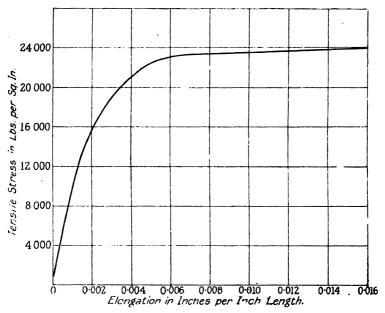
FIG. 14. STRESS-STRAIN CURVE FOR ALUMINIUM WIRE

The hard-drawn aluminium wires used for electric cable construction have a tensile strength of from 10 to 12 tons per sq. in.

Table 14 indicates how the tensile strength varies with the size of the wire.

Fig. 14 shows how aluminium wire behaves during a tensile test; it will be seen that there is no definite elastic limit, but the material continues to stretch for a maximum load of from 50 to 60 per cent of the ultimate value.

Modulus of Elasticity. The modulus of elasticity in the cast form is about 9,000,000 lb. per sq. in., but for the sheet and wire forms it varies from 8,800,000 to 10,700,000 lb. per sq. in.

Compression and Shear. The strength of aluminium in compression for cast cylinders having a length equal to twice the diameter is about 5·4 tons per sq. in., with an elastic limit of about 1·6 tons per sq. in. The maximum shearing stress value for castings is about 5·4 tons per sq. in., and in the drawn condition about 7·15 tons per sq. in.

TABLE 14

STRENGTHS OF ALUMINIUM WIRES

S.W.G.	Diam. (inches)	Tensile Strength (Tons per sq. in.)	S.W.G.	Diam. (inches)	Tensile Strength (Tons per sq. in.)
7/0	0·500	10·2	10	0·128	11·2
4/0	0·400	10·3	12	0·104	11·6
0	0·324	10·3	14	0·080	12·0
2	0·276	10·3	16	0·064	12·5
4	0·232	10·7	18	0·048	12·9
6	0·192	10·7	20	0·036	14·3
8	0·160	11·2			

Strength at Elevated Temperatures

In common with other metals employed for structures and articles under stress, aluminium shows a falling off in tensile strength with temperature increase above atmospheric.

TABLE 15

EFFECT OF TEMPERATURE UPON THE STRENGTH OF ALUMINIUM. (Le Chatelier)

Temp. °C.	15°	100°	150°	200°	250°	300°	400°	450°	460°
Tensile Strength in tons per sq. in.	11·7	9·5	8·1	6·3	4·8	3·6	2·4	1·5	1·0

The elongation increases progressively with temperature increase, as shown by the results given in Table 16.

Aluminium Powders

The term "granulated" aluminium is given to finely divided aluminium produced by blowing molten metal or by grinding in mills. This product consists mainly of particles of more or less spherical

TABLE 16

ELASTIC PROPERTIES OF ALUMINIUM AT HIGH TEMPERATURES
(Martin)*

	Cold-worked Metal						Fully-annealed Metal					
Temperature, °C..	16	100	200	300	400	500	16	100	200	300	400	500
Elongation: Percentage	28·3	28·8	32·8	38·8	79·3	87·0	51·2	62·3	83·9	90·4	127·9	121·4

shape, grease-free and unpolished. It is particularly suitable for use in alumino-thermics and the calorizing process.†

Aluminium powder is made by a stamping, sieving and grading process whereby the metal is finally obtained as minute flat particles which are prevented from welding during the stamping operations by the addition of grease. This powder has important applications in metallic paint, either in its natural colour or dyed with aniline dye to give gold, bronze and other coloured effects. Aluminium paint is made by mixing the powder with a suitable liquid medium, such as oil or spirit varnish, tung oil, cellulose or synthetic resin, lacquers or varnishes; the two latter media represent the more recent methods of making aluminium paint.

When this paint is applied to any moderately smooth surface the various minute laminae of aluminium rise to the surface of the medium and overlap in a somewhat similar manner to the scales of a fish, so as to form a series of thin metallic layers having the properties of a sheet of metallic foil, thus completely protecting the surface below from access of moisture, air or light rays; the latter contain violet and ultra-violet rays which have a deteriorating action on most ordinary paints.

Aluminium paints have wide commercial applications both as protective and decorative coatings for metals, woods and many other materials. Such coatings are also excellent light reflectors, reflecting up to 70 per cent of the light that falls on the surface. For this reason, interiors treated with aluminium paints reflect about the maximum of the incident light, retain their brightness for longer periods than ordinary oil pigment paints, and are cleaner. This paint is used for lamp-posts, sand bins, refuge posts and similar objects which require to remain as conspicuous as possible in dull light.

* "The Tensile Properties of Aluminium at High Temperatures," T. Martin, *Journ. Inst. of Metals*, April, 1924.
† *Powdered and Granulated Aluminium* (Brit. Alumin. Co. publication).

Aluminium paint is also a good heat reflector and therefore tends to keep the surface coated cooler; this helps to prevent the cracking and corrosive action of sun and rain. It is therefore used for such items as oil storage tanks, refrigerator cars, walls of cold storage chambers, explosive filling and storage buildings, aeroplane surfaces, etc. The paint is an excellent primer or base coating for wood and metal surfaces which require protection against corrosion or additional coats of other pigmented paints.

In regard to the selection of the medium for aluminium paint, apart from cellulose and synthetic resin lacquers or varnishes—which give water, oil and petrol proof surfaces—tung oil is recommended as preferable to linseed oil as a base; it gives a waterproof result, better lustre and tougher film. About $2\frac{1}{2}$ lb. of aluminium powder is required for each gallon of medium.

Extremely fine aluminium powder or powder-paste is used for the spraying grades of aluminium paints suitable for producing silver-like surfaces and for coating screens used for cinema projection purposes. When aluminium powder is mixed with bitumen it produces an excellent metal protection paint for outdoor purposes.

Alumino-thermics. There are several commercial applications involving the use of aluminium, whereby the latter is ignited with a metallic oxide in powdered form producing considerable heat, sufficient to melt or even to superheat the molten metal. This method is employed for the reduction of oxide ores of such difficult metals to produce as chromium, titanium, manganese, etc.; the metals are thus obtained with a 98 per cent purity.

The Thermit Process. From the engineering viewpoint the most important application of powdered aluminium is that of welding, for when aluminium is ignited with ferric oxide, the heat generated produces molten iron. The usual proportions employed in the Thermit process, based upon this principle, are three parts of red oxide of iron to one part of powdered aluminium; the weight of the molten iron is about the same as that of the original aluminium. It is somewhat difficult to ignite the powders, but this is achieved by the use of a small firing charge consisting of a mixture of aluminium powder and barium oxide, ignited by means of a fuse. The Thermit process is used in instances where the work has to be done *in situ* and electric or oxy-gas welding cannot conveniently be employed; examples of its application include the welding of tramway and railway lines, broken castings, and forgings.

In the process of Thermit welding the cleaned ends to be united are butted together and surrounded by a mould made from equal parts

of fireclay, fire brick and fire sand. The Thermit is placed in an inverted conical crucible mounted over the butted parts and ignited by the barium-oxide powder on top. When the reaction is completed the molten iron is allowed to flow from the crucible, by removing a plug at the bottom. In order to modify the intense heat—for the reaction temperature may reach 2500° C.—it is usual to mix a certain proportion of steel turnings with the Thermit. It is an advantage to pre-heat the work before allowing the molten iron to flow. When the welding operation is complete and the metal has cooled down, the surplus is removed by grinding or chipping.

CHAPTER III
ALUMINIUM ALLOYS

ALUMINIUM forms an important series of alloys with other metals, including the light aluminium alloys, now so widely used in aircraft, automobile and general engineering, the aluminium bronzes, nitriding steels, a heat-resisting 15 per cent aluminium-iron alloy, etc. It is proposed to devote the present considerations to the lighter alloys, the principal constituent of which is aluminium.

Although aluminium has important industrial applications it is seldom used by itself for aircraft and automobile purposes, except (in the former case) as a corrosion-resisting coating for stronger light alloys. The relatively low tensile, shear and compressive strengths, low impact resistance and hardness of aluminium preclude its employment for engineering purposes in applications requiring high strength-to-weight ratios and satisfactory wearing properties.

When aluminium is suitably alloyed with one or more other metals, of which the most important are copper, magnesium, manganese, silicon and nickel, it forms a series of relatively strong alloys having much greater hardness and impact values than the pure metal.

Although other aluminium alloys were in commercial use at the time, the discovery of duralumin, by Wilm, in 1911, represented the beginning of a new era in hard, strong, aluminium alloys. It contained copper with the addition of small quantities of magnesium and manganese and with special heat-treatment possessed the mechanical properties of low carbon steels. It was also the first alloy of the "age-hardening" class and its introduction led to the initiation of a considerable amount of research work by various authorities, the results of which are evident in the wide range of modern light aluminium alloys. Mention should also be made of the method discovered by Pacz in 1920 for "modifying" cast aluminium alloys by employing an alloy having about 13 per cent of silicon. This modification involves the addition of a small quantity of a constituent, such as sodium, which causes a change in the structure from coarse to fine, so that the eutectic composition is displaced.

It may be mentioned that aluminium can be given increased strength and hardness in three different ways, namely, as follows: (1) The added element can enter into solid solution; (2) it may cause a phase which suitably dispersed throughout the metal forms a rigid skeleton; or (3) it may allow the precipitation of the extremely fine particles

during the heat-treatment procedure, i.e. cause "age-hardening." Of these methods the first is of little utility in the case of modern alloy requirements; the second mode of hardening is found in the casting alloys and the third chiefly in the wrought ones.

The various light alloys of aluminium may conveniently be classified* as follows—

Aluminium-Copper (Cu up to 9 per cent).
Aluminium-Copper-Magnesium (Cu 4; Mg up to 2 per cent).
Aluminium-Copper-Magnesium-Silicon (Cu 4; Mg 2; Si 1·5 per cent).
Aluminium-Copper-Nickel (Cu 4; Ni 2 per cent with additions of Mg and Si).
Aluminium-Magnesium (Mg 5 to 10 per cent with additions of Mn and Sb).
Aluminium-Manganese (Mn up to 2 per cent).
Aluminium-Silicon (Si 8 to 13 per cent with additions of Mg, Mn or Co.).

Aluminium-copper Alloys

The effect of the addition of small percentages of copper to aluminium is to cause an increase in the tensile strength and hardness, but at the same time to reduce the ductility. Usually, the proportion of copper does not exceed about 9 per cent.

The equilibrium diagram of aluminium-copper alloys with copper up to 20 per cent is shown in Fig. 15. It will be observed that at 500° C. aluminium holds about 4·5 per cent of copper in solid solution, whilst at ordinary temperature this is reduced to about 3 per cent. In regard to the microstructure of the alloys in question, those containing more than 2 per cent of copper exhibit in the cast condition a network of $CuAl_2$. As to the mechanical properties of this group of binary alloys some values† are given in Table 17.

TABLE 17

ALUMINIUM-COPPER ALLOYS

TENSILE TESTS‡

Copper per cent	Maximum Stress Tons per sq. in.	Elongation per cent on 2 in.	Hardness (Brinell)	Specific Gravity
0	5·2	37	—	2·70
2	8·2	17	—	2·75
4	9·6	10	—	2·81
6	9·9	5	—	2·85
8	10·6	3	60	2·90
12	—	—	82	—

* "Materials of Aircraft Construction," H. J. Gough, *Journ. Roy. Aeron. Soc.*, 26th May, 1938.

† *Eighth Report, Alloys Research Committee of I.M.E.*, Carpenter and Edwards.

‡ Tests made upon 1 in. diameter chill cast bars.

It will be observed from these results that the tensile strength and specific gravity increase with the copper content, whilst the elongation diminishes.

The alloys most used in practice are those with 6 to 8 per cent copper and with 11 to 13 per cent copper. Typical examples of such
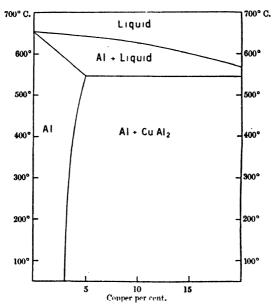

FIG. 15. EQUILIBRIUM DIAGRAM FOR ALUMINIUM-COPPER ALLOYS

alloys are the casting alloys conforming to D.T.D. Specifications 428 and 3L.8, respectively.

The 6 to 8 per cent copper alloy is also represented by the British Engineering Standards Specification No. 3L.11 and the 11 to 13 per cent copper alloy by the Specification No. 2L.8; these, however, have different specifications for the impurities and other elements from those of the D.T.D. Specifications, for which the following are the stipulated percentage compositions—

	Cu	Mg	Si	Fe	Zn	Al
D.T.D. 428	6·0–8·0	0·1	2·0–3·0	1·0	2·0–4·0	Remainder
D.T.D. 3L.8	11·0–13·0	—	0·7	0·8	0·1	[Ti 0·2; Al remainder]

The former alloy has a tensile strength for standard and chill cast bars of 8 and 10 tons per sq. in. respectively, and the latter alloy, 7 and 9 tons per sq. in. respectively; these represent the minimum allowable strength values.

Some physical and mechanical properties of aluminium-copper alloys at elevated and ordinary temperatures are given in Table 18.

TABLE 18

PROPERTIES OF 8 AND 12 PER CENT COPPER-ALUMINIUM ALLOYS

Property	8 per cent Copper	12 per cent Copper
Tensile strength of chill cast alloy at 250° C. (tons per sq. in.)	7·0	6·9
Tensile strength at 350° C.	3·3	4·7
Brinell hardness number (sand cast), 15° C. . .	55	67
Brinell hardness number (sand cast), 300° C. .	11	14
Brinell hardness number (chill cast), 15° C. . .	60	82
Brinell hardness number (chill cast), 300° C. .	12	13
Mass Strength $\left(\dfrac{\text{Max. stress}}{\text{Spec. gravity}}\right)$ in cast condition	3·6	3·1
Mass strength at 350° C. (chill cast) . . .	1·2	1·5
Modulus of elasticity (chill cast), tons per sq. in. .	4200	4200
Thermal conductivity (chill cast), in C.G.S. units .	0·35	0·34
Coefficient of thermal expansion (cast) . .	0·0000231	0·0000184
Shrinkage (inches per foot)	14/100	15/100

Aluminium-copper alloys are employed in industry for light castings requiring greater strength and hardness than ordinary aluminium ones. They have been used for automobile pistons, crankcases, cylinder heads, etc., but more recently the stronger alloys, such as Hiduminium and Y-alloys, have largely taken their place for these purposes.

Aluminium-zinc Alloys

Although previously employed, these alloys are not used to-day since they tend to distort and crack when cast, being subject to *hot-shortness*. An appreciable improvement is effected, however, by the addition of a small proportion of copper. A typical casting alloy of this class has the following percentage composition—

Al, 84·0; Zn, 13·5; Cu, 2·5.

It has a tensile trength (sand cast) of 9 to 11 tons per sq. in., and (chill cast) 11 to 14 tons per sq. in. The corresponding elongations

are 4 to 2 and 8 to 3 per cent, respectively. Such castings are, however, still liable to hot-shortness and to cracking within a few months of casting; they are also heavier than other stronger casting alloys.

Aluminium-silicon Alloys

These alloys are widely used for engineering and other commercial purposes and usually comprise two groups, namely, those with 8 to 10 per cent and 12 to 14 per cent of silicon.
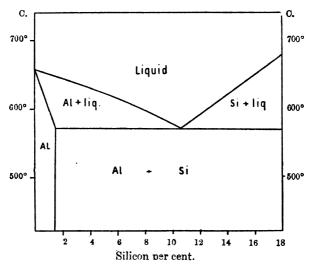

FIG. 16. EQUILIBRIUM DIAGRAM FOR ALUMINIUM-SILICON ALLOYS

Silicon alloys are notable for their low shrinkage value, casting fluidity, clean sharp castings, and good mechanical properties. Moreover, they are among the lightest of the binary alloys of aluminium. They possess good ductility, and are more resistant to corrosion than many other aluminium alloys.

The equilibrium diagram* for aluminium-silicon, for silicon values up to 18 per cent, is shown in Fig. 16. This diagram shows that silicon is only soluble in solid aluminium up to about 1·5 per cent at about 580° C. The eutectic alloy contains about 10·5 per cent silicon.

Fig. 17† shows the normal structure of a chill-cast alloy containing about 12 per cent of silicon. If the melt is treated with a very small

* Hanson and Gaylor, *Journ. Inst. Metals*, 1921; 26, 323.
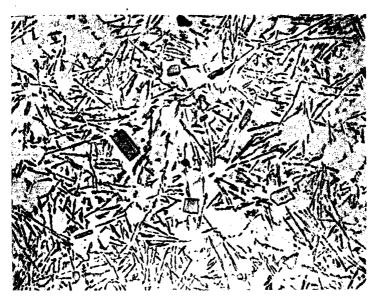† W. Rosenhain and S. L. Archbutt.
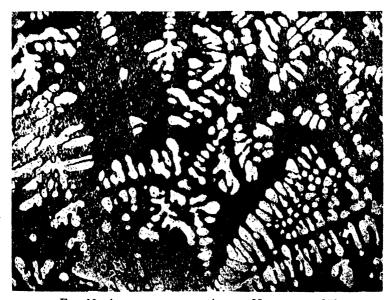
FIG. 17. ALUMINIUM-SILICON ALLOY. UNMODIFIED. × 150

FIG. 18. ALUMINIUM-SILICON ALLOY. MODIFIED. × 150

quantity of sodium or with a flux containing sodium fluoride a modified structure with a very much finer grain is obtained, as shown in Fig. 18; the magnification, it will be observed, is the same in each case.

In regard to the mechanical properties and specific gravities of aluminium-silicon alloys, some test values are given in Table 19.

TABLE 19

PROPERTIES OF TYPICAL ALUMINIUM-SILICON ALLOYS (CAST)

Silicon per cent	Tensile Strength Tons per sq. in.	Elongation per cent	Specific Gravity
8	10·0	10·0	2·67
10	12·5	9·0	2·66
13	14·75	7·5	2·65

Among the commercial aluminium alloys containing silicon as the chief additional constituent may be mentioned Alpax, or Silumin, Lautal (this also contains copper), and Wilmil.

The following typical properties of aluminium-silicon casting alloys (as cast) are given by the British Aluminium Company.

TABLE 20

MECHANICAL PROPERTIES OF ALUMINIUM-SILICON CASTING ALLOYS

Property	Type	10–13 per cent Silicon Alloy
Tensile strength	Sand cast	11–12 tons per sq. in.
	Chill cast	11–15 ,, ,,
Elastic limit (commercial) . . .	Sand cast	5–6 ,, ,,
	Chill cast	6–7 ,, ,,
Per cent elongation in 2 in. . .	Sand cast	5–14 per cent
	Chill cast	8–20 ,,
Brinell hardness (2 mm. ball, 20 kg. load)	Chill cast	55–65
Izod impact test	Sand cast	3–7 ft.-lb.
	Chill cast	4–10 ,,

By *suitable heat-treatment* the mechanical properties can be improved considerably in many instances. Thus, in the case of Alpax "Beta" (Si, 10·0–13·0 per cent; Mg, 0·6 per cent; Mn, 0·6 per cent) as cast, the alloy has about the same strength properties as the alloys given in Table 20. When, however, it is heat-treated by heating for 2 to 4 hours at 530° C. and quenched, afterwards being heated for

16 hours at 160° C. and quenched, the minimum tensile strengths in the sand and chill cast states are 15·5 and 19·0 tons per sq. in., respectively. The 0·1 per cent proof stress values are 13 and 16 tons per sq. in. respectively.

These alloys are more resistant to corrosion than most other aluminium alloys, and have been used on ships and in similar locations where corroding conditions are severe.

The ductility of these alloys in the cast state is high for light alloys, so that the castings are, to some extent, malleable and can be bent without cracking.

The alloys in question have a very low solidification contraction and are not "hot-short," so that casting is simplified. Their good casting qualities make them particularly suitable for castings which have thin sections of large area, sudden changes in section, or containing steel insets of large diameter.

The ordinary aluminium-silicon alloys used for commercial purposes are poured at about 700° C.; in no cases should the metal be allowed to exceed 750° C. during the melting process prior to pouring. In connection with die-casting work, these alloys are affected by their rate of freezing, or solidifying, in the mould; for this reason they are particularly suited for chill and die-casting purposes. The dies should be kept heated at about 200° C.

These alloys can be forged and rolled, suitable working temperatures being about 450° to 460° C. For annealing the recommended temperature is 450° to 500° C. Actually, however, forged and rolled aluminium-silicon alloys are not used to any extent commercially, on account of their relatively low mechanical strength and elastic limit; the former is of the order of 10 to 12 tons per sq. in. with from 7 to 11 per cent elongation.

Silicon alloy sheet is supplied by the British Aluminium Company under the name No. 40D alloy. It is supplied in three grades or tempers, viz., hard, medium, and soft. The following are the average mechanical properties of these grades—

TABLE 21
PROPERTIES OF ALUMINIUM-SILICON ALLOY SHEETS

Temper	Tensile Strength Tons per sq. in.	Percentage Elongation in 2 in.
Hard	12–14	5–9
Medium . . .	10–12	10–15
Soft	9–10	20–30

Of these three the medium temper is most commonly used when a moderate amount of shaping is to be done. Medium sheets are capable of being bent through 180° round a radius equal to the thickness of the sheet.

The specific gravity of the alloy is 2·67. The medium temper sheet can be softened by annealing (by heating to about 350° C.) and it is hardened by cold working. It cannot be hardened by any process of heat-treatment or ageing.

Aluminium-magnesium Alloys

Although magnesium enters into the composition of many of the more complex aluminium alloys considered in this section, there is an interesting series of binary alloys which possesses certain advantages for aircraft and similar purposes.

As magnesium is appreciably lighter than aluminium, the alloys formed with the latter metal are lighter than aluminium and the other alloys under consideration.

Thus, the specific gravities of aluminium-magnesium alloys with 2, 4, 6, 8, 10, 12, and 14 per cent magnesium content are respectively 2·681, 2·661, 2·641, 2·621, 2·601, 2·582 and 2·562; for aluminium itself the corresponding specific gravity is taken as 2·702.

The binary alloys in question are much *more resistant to corrosion* than aluminium or the light alloys mentioned in this section; in this connection the present useful range includes alloys with magnesium up to about 15 per cent.

TABLE 22

EFFECT OF MAGNESIUM ON THE MECHANICAL PROPERTIES OF
ALUMINIUM (WROUGHT AND ANNEALED)

Magnesium per cent	Proof Stress Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation per cent
0	2·0	6·20	40·0
1	6·0	9·50	29·0
2	6·45	11·50	25·0
3	6·92	13·60	24·0
4	7·65	15·00	24·0
5	8·30	17·15	22·0
6	9·60	20·00	22·0
7	10·75	22·50	21·0
8	12·20	24·50	21·0
9	13·10	25·80	20·0

In regard to the effect of magnesium upon the strength properties of aluminium, from the values given in Table 22, due to L. Aitchison,

it is apparent that the proof stress and tensile strength increase practically in proportion to the magnesium content, whilst the elongation diminishes in inverse proportion. The values in question refer to the wrought alloys in the annealed condition.

In connection with the corrosion resistance this appears to be a linear function of the magnesium content, so long as the magnesium can be kept in solid solution; the best alloys from this viewpoint are those having 5 and 7 per cent of magnesium, known as MG.5 and MG.7 respectively.

An important alloy having excellent mechanical properties without the necessity of heat-treatment is one containing 7 per cent of magnesium and 0·25 per cent of manganese. It has the following minimum mechanical properties—

TABLE 23

PROPERTIES OF ALUMINIUM-MAGNESIUM ALLOY

Condition	Tensile Strength Tons per sq. in.	0·1 per cent Proof Stress Tons per sq. in.	Elongation per cent
Annealed . . .	20	10	20
Cold-rolled . .	25	15	15

This alloy work-hardens appreciably. It has a good resistance to corrosion in marine waters and atmospheres. It can be obtained commercially in sheet, rolled sections, rivets, etc.

Another important alloy is the binary one with 5 per cent of magnesium. It is particularly suitable for rivets and wire; the latter can be made with a tensile strength of 16 tons per sq. in. and rivets can be formed from it more conveniently than from the heat-treatable alloys, such as duralumin.

A commercial alloy of the aluminium-magnesium class, which is actually used for the plates or skins of metal boats, is Birmabright. It has a high degree of corrosion resistance; a proof stress of 20·5 tons per sq. in.; tensile strength of 23·9 tons per sq. in., and elongation of 3 per cent. The MG.7 alloy has a proof stress of 17·50 tons per sq. in.; tensile strength of 24·9 tons per sq. in., and elongation of 14·0 per cent.

The MG.9 alloy has a proof stress of 12·5 tons per sq. in.; tensile strength of 25·4 tons per sq. in., and elongation of 21·0 per cent.

In each of the above alloys the results refer to the cold-worked metal.

Aluminium-manganese Alloys

The addition of small proportions of manganese to aluminium improves the resistance to corrosion and renders the metal readily weldable. A typical alloy is the one known as BA/60A, which contains $1\frac{1}{4}$ per cent of manganese. It is supplied in sheet and strip form in five tempers, namely, Soft, Quarter-hard, Half-hard, Three-quarter Hard, and Hard. These alloys are non-heat-treatable ones.

The tensile strengths of these tempers are as follows: 6·0–7·5; 7·5–9·5; 9·0–11·0; 11·0–13·0 and 13·0 (min.) tons per sq. in.

The 0·1 per cent proof stresses (average) are: 2·7, 7·6, 8·9, 10·4 and 10·75 respectively.

The corresponding elongations are: 22–45; 4 to 7; 3 to 10; 2 to 8; 2 to 6 per cent.

In this connection it should be mentioned that for any of the grades the elongation depends also upon the actual thickness of the sheet.

The Brinell hardnesses range from 27 for the soft temper to 54 for the hard one.

The specific gravity of this alloy is 2·73.

Other Corrosion-resistant Alloys

An aluminium alloy having 2·5 per cent of magnesium and 0·25 per cent of manganese possesses a high resistance to corrosion and, in addition, can be worked with comparative ease in the annealed condition. It has then a tensile strength of 12·5 tons per sq. in. and elongation of 20 per cent. This alloy is supplied in sheet form and also for soft tubes for petrol and oil conveyance purposes on aircraft. Another interesting alloy* is one containing chromium and magnesium, a typical composition being 1·5 to 3·0 per cent of the latter to 0·1 to 0·35 per cent of the former. It has about the same strength properties as the alloy previously mentioned and has also a high resistance to corrosion.

The "clad" duralumin and improved duralumin alloy sheets, with pure aluminium coatings, may also be referred to in connection with the other as corrosion-resistant, high-strength sheet alloys.

Classification of Aluminium Alloys

Modern aluminium alloys now embrace a relatively large number of compositions, and are known by various B.S.I., D.T.D. Specifications and proprietary names. Such alloys may be identified in general by their chemical compositions and in this connection the classification system given on page 35 will be found helpful.

* *Ante,* page 11, note.

For commercial application purposes, however, it is more convenient to consider the light aluminium alloys as belonging to three definite groups, namely, as follows: (1) *Heat-treatable alloys containing copper and magnesium.* (2) *Heat-treatable alloys without copper.* (3) *Alloys that are not heat-treatable, under the main classes of wrought and cast alloys.*

The first group of wrought alloys includes duralumin, Super-duralumin, Hiduminium R.R. and Y-alloys to which more detailed reference is given later. Mention should here be made of *a more recent alloy* in this group,* now in commercial production, which gives *excellent mechanical properties* for its specific gravity of 2·8. The following is the percentage composition: Cu, 1·5–3·5; Fe, 0·6; Mg, 2–4; Zn, 4–6; Ni, ≯ 1·0; Si, ≯ 0·6; and Ti, ≯ 0·3.

After solution heat-treatment at 460° C., followed by age-hardening treatment, at 130° C., this alloy has a tensile strength of 33 to 38 tons per sq. in. with 0·1 per cent proof stress of 28 to 33 tons per sq. in.; elongation of 10 to 18 per cent, and Wöhler fatigue range of ± 12·5 tons per sq. in.

The second group includes alloys having a nominal percentage composition as follows: Si, 1·0; Mg, 0·6; Mn, 0·75 (may be omitted); Al, remainder.

In order to develop the full mechanical properties the alloy is heated to 520° C. and quenched in water. After being allowed to age-harden at normal air temperatures the metal has a minimum tensile strength of 17 tons per sq. in. with 20 per cent elongation; it has a 0·1 per cent proof stress of 10 tons per sq. in. It is also possible to subject the alloy to precipitation heat-treatment. Thus, after quenching from 520° C. it is treated at 165° C. and has a tensile strength between 20 and 23 tons per sq. in. and corresponding elongation of 10 to 15 per cent; the 0·1 per cent proof stress is 15 to 19 tons per sq. in.

Applications of this medium strength alloy include pressed sheet metal parts for aircraft, e.g. cowlings and fairings.

The third group includes alloys containing magnesium up to about 10 per cent with small percentages of manganese, tin or chromium.

These alloys have previously been referred to under the headings of Aluminium-magnesium and Aluminium-manganese Alloys.

The Wrought Aluminium Alloys

A convenient method of classifying the wrought alloys is that based upon the heat-treatment† and it has the advantage of requiring only three groups to cover a very wide range of commercial alloys.

Ante, page 11, note.
† "Wrought Alloys of Aluminium in Aircraft," G. Mortimer, *Aircraft Engineering*, September, 1929.

These groups are as follows—

(1) Alloys having magnesium silicide (Mg_2Si) as the hardening medium.

(2) Alloys having copper eutectic compound ($CuAl_2$) as the hardening medium.

(3) Alloys having magnesium silicide and copper eutectic combined as the hardening medium.

It is here necessary to explain that for the stronger light aluminium alloys the principle of heat-treatment is the same. For all such alloys there is some constituent which is not only soluble in solid aluminium but of which the primary aluminium crystals will absorb more at high temperature than at ordinary temperatures. This constituent is normally present in excess in the alloy, and the first stage of heat-treatment consists in holding the alloy at a suitable temperature until this excess is absorbed into solid solution. The operation of quenching fixes the excess in solution, the alloy then being in an unstable state. The excess in solution tends to precipitate, and, under suitable conditions, is thrown down in a finely dispersed state—a process associated with the previously mentioned phenomenon known as age-hardening.

(1) Magnesium Silicide Group

This essential constituent of the first group of alloys is usually present, due to the inclusion of a small percentage of silicon in commercial aluminium; the added magnesium results in the formation of

TABLE 24

COMMERCIAL ALUMINIUM ALLOYS

Group 1. Hardening Medium Mg_2Si (Mortimer)

Trade Name	Approx. Essential Composition, with Iron Normal, and Aluminium Remainder				Commercial Range of Mechanical Properties
	Mg	Mn	Si	C	
Aldrey . .	0·6	0·6	1·0	—	After heat-treatment all of these alloys offer much the same properties. A tensile strength of 20–22 tons, elongation of 6–18 per cent and a Brinell hardness of 80–100; actual figures vary with treatment, with section and with percentage reduction in working.
Almalec	0·6	0·6	1·0	—	
Silmalec .	0·6	0·6	1·0	—	
51S . .	0·6	0·6	1·0	—	
Anticorodal .	0·6	0·6	1·0	—	
Aludur . .	0·6	—	0·88	—	
Almasilium .	1·0	—	2·0	—	
Montegal	0·95	—	0·8	0·2	

Mg_2Si, a compound of which at room temperature only about 0·3 per cent is soluble in aluminium. At about 580° C., however, as much as 1·6 per cent can be absorbed. The effect, then, of heating the alloy to 580° C. and then quenching is to cause the Mg_2Si to be absorbed in excess. Subsequent hardening, or "ageing," causes a precipitation of the excess in a finely divided state.

The normal heat-treatment of this group of aluminium alloys is to quench from 510°–520° C. in cold water, following this by annealing for 12 to 24 hours at about 160° C. In order to obtain the soft annealed condition the metal is heated or "soaked" for a time at 350° C. and allowed to cool slowly.

(2) Copper Eutectic Compound Group

When copper is added to commercial aluminium about 1 to 2 per· cent is normally retained in solid solution. By soaking at 540° C. for some hours, however, as much as 5·5 per cent of copper may be brought into solution and fixed by quenching, and the effect of this can be seen clearly through the microscope, in the partial or entire disappearance of the characteristic network of eutectic compound. Since the maximum absorption possible is in the neighbourhood of 5·5 per cent of copper, the known alloys of this series contain about 4 per cent of copper, to ensure a minimum of eutectic at the crystal boundaries after heat-treatment.

TABLE 25

COMMERCIAL ALUMINIUM ALLOYS
Group 2. Hardening Medium $CuAl_2$ (Mortimer)

Trade Name	Approx. Essential Composition, with Iron Normal, and Aluminium Remainder			Commercial Range of Mechanical Properties
	Cu	Mn	Si	
Lautal	4·0	—	2·0	Properly worked and heat-treated, these alloys will give in practice a tensile strength of 24–25 tons per sq. in. with 18–20 per cent elongation, and a Brinell hardness of 90–100.
Aeron	4·0	—	2·0	
25S	4·0	0·8	0·8	
L.M.	4·75	0·75	0·75	

These alloys do not harden spontaneously, and they are usually supplied, commercially, in the quenched but unhardened state. To bring about precipitation and the best physical properties the metal

is either soaked for about 16 hours at 120°–130° C. or for about 48 hours at 140°–150° C. In the first case the treatment will give a tensile strength of about 22 tons per sq. in., with 25 per cent elongation; in the second it will give about 24 to 25 tons per sq. in. with 18 to 20 per cent elongation.

To *anneal* the alloy it is allowed to soak for some time at 350°–400° C., and then cooled slowly.

To *re-harden* it is quenched from 490°–510° C. The *forging* temperature is 440°–480° C., and several intermediate heatings are advisable in heavy reductions.

(3) Combined Hardening Media Group

In this group the hardening influence of both Mg_2Si and $CuAl_2$ are involved. Amongst these alloys we have duralumin and Super-duralumin, two of the strongest aluminium alloys known. The addition of nickel confers valuable frictional qualities and the property of maintaining strength and stiffness at high temperature; there is as yet no alloy quite so good as "Y"-alloy for pistons, and it is also used for such parts as the connecting rods and cylinder heads of air-cooled engines. Silicon, which has obviously been added to many of the alloys in all three groups in excess of that normally expected as an impurity, improves both the foundry and working properties. Manganese tends slightly to refine the grain. Cadmium, it is claimed by some authorities, increases the resistance to sea-water corrosion.

TABLE 26

COMMERCIAL ALUMINIUM ALLOYS

Group 3. Hardening Medium $Mg_2Si + CuAl_2$ (Mortimer)

Trade Name	Approx. Composition, with Iron Normal, and Aluminium Remainder						Commercial Range of Mechanical Properties
	Cu	Mg	Mn	Si	Cd	Ni	
Duralumin . .	4·0	0·5	0·5	0·6	---	---	Between 25 and 35 tons per sq. in. with 15–20 per cent elongation.
Aldal . . .	4·0	0·5	0·5	0·6	---	---	
17S . . .	4·0	0·5	0·6	0·3	---	---	
Almag . . .	2·5	0·7	—	0·6	---	---	
Alferium . .	3·5	0·6	0·5	0·3	---	—	
"Y"-alloy . .	4·0	1·5	—	0·4	---	2·0	
Aeral . . .	3·5	1·8	—	0·6	2·25	—	
Avional . .	4·75	0·5	1·0	1·4	—	—	
Super-duralumin .	4·0	0·5	0·5	0·75	---	—	

Standard and Commercial Wrought Alloys

The compositions, heat-treatments and minimum tensile strengths, proof stress (0·1 per cent), and elongations of a number of the most widely used wrought alloys of aluminium, together with indications of their applications, are conveniently given in Table 27,* pages 50–55.

The Directorate of Technical Development (D.T.D.) Air Ministry Specifications and also the corresponding proprietary makes or names of these alloys are given in columns 3 and 1, respectively.

Some further notes on certain of these alloys are given later in this chapter.

Aluminium Alloys for Castings

The various D.T.D. standard and equivalent commercial casting alloys of aluminium are conveniently classified for reference purposes in Table 28,† pages 56 and 57, which also indicates the principal applications of such alloys.

Duralumin

This widely used alloy containing copper, magnesium and silicon is the strongest aluminium alloy that can be produced by age-hardening at room temperature. The percentage chemical composition is approx-
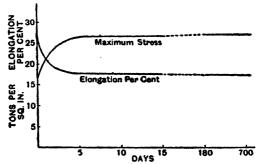
FIG. 19. EFFECT OF AGE-HARDENING ON PROPERTIES OF DURALUMIN

imately as follows: Cu, 4·0; Mn, 0·5; Mg, 0·5; Si, 0·25 to 0·60; Al (the remainder).

The standard heat-treatment consists in quenching it from 480° to 500° C. in water and allowing it to age at room temperature.

The manner in which the tensile strength increases with the period of time from quenching is illustrated in Fig. 19‡. The maximum stress

* Courtesy, British Aluminium Co.
† Courtesy, Northern Aluminium Co.
‡ "Strong Light Alloys of To-day," L. Aitchison, *Proc. Inst. Autom. Engrs.* March, 1933.

TABLE 27
WROUGHT ALUMINIUM ALLOYS

Common Designation	Nominal Composition*	Specification No.	Description and Heat-treatment	Minimum Tensile Strength Tons per sq. in.	0·1 per cent Proof Stress Tons per sq. in.	Elongation per cent in 2 in.
MG. 7	Mg. 6·5–10·0% Mn. 0·6% Max. Si. 0·5% „ Fe. 0·75% „	177A	Sheets (Hard) .	25	17	Over 0·104 in. 15
		182A	Sheets (Annealed) .	Min. 20 Max. 23	10	Over 0·104 in. 20
		186A	Tubes (Hard) .	0·104 in. thick and under 26 Over 0·104 in. 25	18	—
		190	Tubes (Annealed) .	Min. 20 Max. 23	17	—
		194	Bars .	Up to 1 in. 25 1 in.–3 in. 22 Over 3 in. 21	10	15 15 15
		297	Bars, Extruded Sections and Forgings (Softened) .	20	8	15

Alloy	Composition*	Spec. No.	Form and condition			
Birmabright and R.R.6	Mg. 3·0-6·0% Mn. 0·75% Max.	170A	Sheets (Hard)	20	15	Over 0·104 in. 3
		175A	Sheets (Half-hard)	16	12	Over 0·104 in. 6
		180A	Sheets (Soft)	14	—	Over 0·104 in. 20
Birmabright II D.2 and NA.4S	Mg. 3·0% Max. Mn. 1·5% ,,	249	Sheets (Hard)	16	14	Over 0·104 in. 5
		266	Sheets (Half-hard)	14	12	Over 0·104 in. 5
		209A	Sheets (Soft) Birmabright II and D.2	12	—	Over 0·104 in. 18
		278	Sheets (Soft) (NA.4S)	11	—	Over 0·104 in. 18
R.R.56	Cu. 1·5-3·0% Ni. 0·5-1·5% Mg. 0·4-1·0% Fe. 0·8-1·4%	179 and 184	Airscrew Forgings H.T.—2 hr. at 520-535° C. and quenched. 15-20 hr. at 165-175° C. and quenched	27	20	10
		206	Sheets H.T.—Heated at 530 ± 5° C. and quenched. Not less than 16 hr. at 170 ± 5° C. and quenched	27	21	Over 0·104 in. 10
		220A	Tubes H.T.—Heated to 530 ± 5° C. and quenched. 10-20 hr. at 170 ± 5° C. and quenched	27	(0·2% proof stress) 23	Under 0·064 in. 6 / 0·064 in. to 0·104 in. 8 / Over 0·104 in. 10

* In each of the above alloys the remainder consists of aluminium and normal impurities.

					Over 0·020 in.	Over 0·104 in.
T, Ceralumin F and NA.15S	Ni. 0·5-2·0% Mg. 0·5-1·25%		H.T.—Heated at 510-535° C. and quenched. 10 hr. at 150-175° C. and quenched			
B.A.60A	Mn. 1·5% Max. Cu. 0·15% ,, Fe. 0·75% ,,	213	Sheets (Three-quarter Hard) .	11	—	—
Duralumin	Cu. 3·5-4·5% Mn. 0·4-0·7% Mg. 0·4-0·7%	395 (4L.3)	Sheet H.T.—Heated to 490 ± 10° C. and quenched. Then aged at room temperature for 5 days	25	Over 0·020 in. 15	Over 0·104 in. 15
		477 (5L.1)	Bars for machining (up to 3 in.), Extruded Sections and Forgings H.T.—As for 395 above .	25	15	15
		L.39	Bars for machining (3 in.-6 in.) . H.T.—As for 395 above .	22	12	15
		396 (4T.4)	Tubes . H.T.—As for 395 above .	26	18	0·064 in. and under 8 0·064 in. to 0·104 in. 10 Over 0·104 in. 12·5
		532	Forgings . H.T.—Heated to 480-490° C. and quenched. Then aged at room temperature for about 4 days	2⅝ in. and under 25 Over 2⅝ in.-4 in. 22 Over 4 in.-6 in. 20 Over 6 in. 18	14 11·5 10·5 9	15 15 15 15

* In each of the above alloys the remainder consists of aluminium and normal impurities.

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TABLE 27—(concluded)

Common Designation	Nominal Composition*	Specification No.	Description and Heat-treatment	Minimum Tensile Strength Tons per sq. in.	0·1 per cent Proof Stress Tons per sq. in.	Elongation per cent in 2 in.
"Y"-Alloy	Cu. 3·5–4·5% Ni. 1·8–2·3% Mg. 1·2–1·7%	414	Sheet H.T.—Heated to 500–520° C. and quenched. Then aged at room temperature for 5 days	23	14	Below 0·020 in. 8 0·020 in. to 0·048 in. 12 Over 0·048 in. 15
		478 (3L.25)	Bars for machining (up to 3 in.), Bars for forging and forgings H.T.—Heated to 490–525° C. and quenched. Aged at room temperature for 5 days	24	14	15
		533	General Forgings H.T.—Heated to 505–520° C. and quenched. Aged at room temperature for 5 days	$2\frac{3}{8}$ in. and under 24 Over $2\frac{3}{8}$ in.–4 in. 22 Over 4 in.–6 in. 20 Over 6 in. 18·5	13 11·5 10·5 9	15 15 12 10
		L.43	Drop Forgings (pistons and cylinder heads). H.T.—As for 478 above	22	—	8
Hidu-minium R.R.56	Cu. 1·5–2·9% Ni. 0·5–1·5% Mg. 0·6–1·2% Fe. 0·8–1·5%	L.40	Bars for machining (up to 3 in.). Bars for forging and forgings H.T.—Heated to 510–535° C. and quenched. 10–20 hr. at 155–175° C.	27	21	10
Hidu-minium R.R.59	Cu. 1·5–3·0% Ni. 0·5–1·5% Mg. 1·2–1·8% Fe. 1·0–1·5%	L.42	Drop Forgings H.T.—As L.40 above	25	—	6

* In each of the above alloys the remainder consists of aluminium and normal impurities.

TABLE 28

ALUMINIUM CASTING ALLOYS

Specn.	Proprietary Names	Composition per cent† (Aluminium remainder)										Minimum Mechanical Properties					
		Cu	Mn	Mg	Si	Fe	Ti	Ni	Cr if present	Zn	Others	0·1% Proof Stress Tons/sq.in.		Ultimate Tensile Stress Tons/sq.in.		Elongation % on 2 in.	
												*Std. Test Bar	*Chill Cast	*Std. Test Bar	*Chill Cast	*Std. Test Bar	*Chill Cast
D.T.D. 131A	R.R.58 (H.T. pistons)	1·5-2·5	—	1·3-1·7	2·0	0·8-1·3	0·02-0·12	0·5-2·0	—	—	—	15·5	19	16	20	1·	—
133B	R.R.50 (not pistons)	0·8-2·0	—	0·05-0·3	1·5-2·8	0·8-1·4	0·05-0·25	0·8-1·75	—	—	—	7·5	8	11	12·5	2·5	4
165	Birmabright	—	0·25-0·75	3·0-6·0	—	0·6	—	—	—	—	—	5	5	9	11	3	5
231	NA.160, BA/40D, MVC., Wilmil M	—	0·5	—	8·0-12·0	0·6	0·2	—	—	0·1	1·0 incl. Fe	3	4·5	10	12	7	7
238	R.R.53 (as cast)(pistons)	1·5-2·5	—	1·4-1·8	2·0	1·2-1·5	0·02-0·12	0·5-2·0	—	—	0·1 + mod. 0·3	8	8·5	9	12	—	—
240	NA.161/A.3, Alpax Beta, Wilmil M (H.T.)	—	0·6	0·6	10·0-13·0	0·6	—	—	—	—	0·2	6	8·5	11	15	1·5	3
245	NA.161/T69, Alpax Gamma, BA/40M, Wilmil M (fully H.T.)	—	0·6	0·6	10·0-13·0	0·6	—	—	—	—	0·2	13	16	15·5	19	—	'·
250	NA.211/W.64, Ceralumin D (not pistons)	2·0-3·0	—	0·5-1·0	1·0-1·4	1·0-1·4	—	1·0-2·0	0·05-0·2	—	if present Ce 0·05-0·2 Cb 0·05-0·3	11·5	13	14	20	—	5
255	NA.211/T.64, Ceralumin C (pistons)	2·0-3·0	—	0·5-1·0	1·0-1·4	1·0-1·4	—	1·0-2·0	0·05-0·2	—	if present Ce 0·05-0·2 Cb 0·05-0·3	17·5	20	18	23·5	—	—
264	NA.158, Birmasil Special (not pistons)	0·1	0·5	—	10·0-13·0	0·6	0·2	2·5-3·5	—	0·1	—	4·5	6	12	16	2	3
269	NA.222/T.20	4·0-4·6	0·3	0·1-0·3	0·7-0·9	0·5-0·7	0·25	—	—	—	—	13	14	18	19	—	—
272	NA.125/W.60 (not pistons)	1·0-1·5	—	0·4-0·6	4·5-5·5	0·6	0·25	—	—	—	—	8	10	11	13	2·	—
276	NA.125/T.67 (not pistons)	1·0-1·5	—	0·4-0·6	4·5-5·5	0·6	0·25	—	—	—	—	11	13	15·	17	—	—
287	NA.111 Ceralumin B (not pistons)	1·0-2·0	—	0·05-0·2	0·75-2·5	0·25-1·3	—	1·0-1·75	0·05-0·3	—	Ce 0·05-0·3 Cb 0·05-0·3	7·5	8	10	12·5	2	4
294	Aerial "A" (not pistons)	2·0-4·5	0·5	0·2-1·5	2·5	0·8	0·4	—	—	—	if present Cd 0·5-2·5	11	12	14	17	3	5
298	NA.226 (226/W.91) (not pistons)	4·0-5·0	Imps.	Imps.	0·9	0·7	0·25	Imps.	—	Imps.	Total Imps. ≯ 0·2	11	15	14	18	7	10

Spcn.	Proprietary Names	Composition per cent† (Aluminium remainder)									Minimum Mechanical Properties					
		Cu	Mn	Mg	Si	Fe	Ti	Ni	Zn	Others	0.1% Proof Stress Tons/sq.in. *Std. Test Bar	*Chill Cast	Ultimate Tensile Stress Tons/sq.in. Std. Test Bar	*Chill Cast	Elongation % on 2 in. Std. Test Bar	*Chill Cast
D.T.D. 300	N.A.350, BA/29 (not pistons)	0·15	Imps.	9·5-10·5	0·25	0·3	Imps.	—	—	Total Imps. incl. Ca > 0·25	11	13	16	18	7	12
304	N.A.226 (226-T.92) (not pistons)	4·0-5·0	Imps.	Imps.	0·9	0·7	0·25	Imps.	Imps.	Total Imps. > 0·2	14	17	18	24	4	0
309	B.R.53C (H.T.) (not pistons)	0·8-2·0	⌡	0·3-0·8	2·0-3·0	0·8-1·4	0·3	0·5-1·5	—	—	18	19	19	22	2	—
313	R.R.53C; as cast (not pistons)	0·8-2·0	—	0·3-0·8	2·0-3·0	0·8-1·4	0·3	0·5-1·5	—	—	5	6·5	10	13	2	—
361	N.A.226 (H.T. sand) (not pistons)	4·0-5·0	Imps.	Imps.	0·9	0·7	0·25	Imps.	Imps.	Total Imps. > 0·2	20	22·5	21	26	1	4
424	N.A.117, General Purpose Alloy	2·0-4·0	0·7	0·15	3·0-6·0	0·8	—	0·35	0·2	—	5	5	9	10	2	2
428	N.A.237, Alloy for Low Stressed Parts	6·0-8·0	Imps.	0·1	2·0-3·0	1·0	—	Imps.	2·0-4·0	Total Imps. inc. Sn and Pb 1·0	5	—	8	10	2	—
B.S.S.3L.5	N.A.465	2·5-3·0	—	—	0·7	0·8	0·2	—	12·5-14·5	Pb 0·1	3·5	3·5	9	11	2	3
3L.8	N.A.260, Birmal L.8	11·0-13·0	—	—	0·7	0·8	0·2	—	0·1	Pb 0·1	4·5	3·5	7	9	—	3
4L.11	N.A.232	6·0-8·0	—	—	0·7	0·8	0·2	—	0·1	Pb 0·1 Sn 1·0	3·5	3·5	7·5	9	1·5	—
2L.24 L.33	N.A.218, "Y" Alloy N.A.160, Alpax, BA/401, Birmasil, WilmlM	3·5-4·5	—	1·2-1·7	0·6 {1·0	0·6	0·2	1·8-2·3	·Sn 0·1	Pb 0·05	8·5	8·5	10	12	—	—
	(cont.)	—	0·5	—	10·0-13·0 {1·0	0·6	0·2	—	0·1	0·1 + mod. 0·3	3·5	4·5	10·5	13	5	8
L.35	N.A.218, "Y" Alloy, Birmidium (H.T.)	3·5-4·5	—	1·2-1·7	0·6	0·6	0·2	1·8-2·3	·Sn 0·1	Pb 0·05	13	14	14	18	—	2

† Single figures show maximum content.
* For information purposes only.
Imps. Impurities. Where this appears under the heading of an alloying element it indicates that the element concerned may be present as an impurity.
N.A. denotes Northern Aluminium aluminium alloys.

Mod. Modifying agent', i.e. Na, Wo, Cr, Co, B, Ca.
H.T. Heat-treated.

curve shows that the tensile strength directly after quenching is about 16·5 tons per sq. in., and that the tensile strength increases progressively until after 6 to 7 days of "ageing" it attains a value of about 27 tons per sq. in. Actually, the tensile strength continues to increase beyond this value with further periods of time, for the curve of maximum stress is asymptotic to a line parallel to the time axis. Over a period of two years it has been shown that the strength of the alloy rises by about 1 ton per sq. in. as compared with its strength at the end of 7 days from quenching. With this increase in tensile strength there is a corresponding reduction in the ductility; thus at quenching the elongation is about 27 per cent, falling in 6 to 7 days to about 17·5 per cent, and thereafter continuing to fall at a much lower rate.

The principal advantages claimed for duralumin are summarized by Aitchison as follows—

(1) The temperature employed for the solution heat-treatment of the alloy is the lowest that is applicable to any commercial light alloy.

(2) The alloy is soft enough for a workable period after it has been quenched, i.e. the rate of age-hardening is not sufficiently great to prevent a certain amount of mechanical work being carried out before it becomes too hard.

(3) It hardens spontaneously when exposed to room temperatures. This has definite practical advantages as a second heat-treatment is avoided.

In regard to the *effect of reheating the age-hardened metal* to various temperatures, i.e. subjecting it to precipitation heat-treatment, the results of tests made upon duralumin are given in Table 29.

TABLE 29

EFFECT ON MECHANICAL PROPERTIES OF REHEATING
DURALUMIN

Temperature °C.	Tensile Strength (Tons per sq. in.)	Elongation per cent
20	28·65	18·7
100	27·69	18·6
125	27·33	19·9
150	27·08	20·3
175	27·04	17·7

The general mechanical properties of duralumin in the forged and age-hardened condition, derived from tests* made on a standard

* "Commercial Aluminium Alloys," J. B. Hoblyn, *Proc. Inst.Autom. Engrs.*, 1929–30.

B.S.I. test bar, are given herewith—

Ultimate stress	28·64 tons per sq. in.
Yield point	18·00 tons per sq. in.
Elastic limit with permanent set	} 10·00115 in. on 2 in. } 16·20 tons per sq. in.
Proof stress with permanent set	} 0·003 in. on 2 in. } 17·00 tons per sq. in.
Elongation	18·5 per cent.
Reduction of area	36·4 per cent.
Average Izod value	24 ft.-lb.
Brinell number	114
Modulus of elasticity	10×10^6 lb. per sq. in. in extension.
Modulus of elasticity	$10·63 \times 10^6$ lb. per sq. in. in compression.

The Brinell hardness varies with the quenching temperature and time period after quenching, as shown by the results given in Fig. 20.
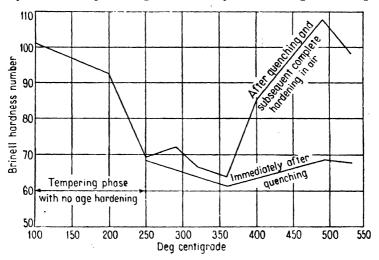
FIG. 20. EFFECT OF WATER QUENCHING DURALUMIN IN THE "AS RECEIVED" CONDITION

It will be seen that the metal is in its softest condition as quenched from 360° C. immediately after quenching. Further, on quenching age-hardening duralumin from temperatures below 250° C. the hardness is reduced and there is no age-hardening effect.

Duralumin is supplied in all forms in which steel is available, i.e. sheets, bars, tubes, girders, drop stampings and forgings of various kinds; it cannot be cast satisfactorily. The metal is generally supplied in the age-hardened condition and for sheet metal bending and spinning

purposes it is annealed by quenching at 360° to 380° C. immediately beforehand; the annealing operation should be done as quickly as possible and with the minimum of "soaking" at the temperature mentioned.

Duralumin sheets, rivets, wire, etc., that are to be cold-worked may be annealed and then *stored in a refrigerator, when age-hardening is postponed* until the alloy is again exposed to normal air temperatures.

Forging or hot stamping is effected on metal supplied in the untreated condition at temperatures between 420° and 440° C.; a relatively slow period of heating to this temperature is desirable.

Physical Properties of Duralumin

The following particulars relate to the alloy (supplied by Messrs. Vickers, Ltd.)—

Specific gravity	2·8
Coefficient of linear expansion	22·6 × 10^{-6} per °C.
Specific heat	0·214 (water = 1·0)
Thermal conductivity	31 (silver = 100)
Melting point	650° C.
Electrical conductivity—	
Age-hardened	33–35 per cent of copper
Annealed	39–41 per cent of copper
Young's modulus of elasticity	10 × 10^6 lb. per sq. in.
Brinell hardness—	
Annealed	60
Age-hardened	100
Fatigue range	± 9·5 tons per sq. in.
Impact value	15 ft.-lb.

Applications of Duralumin

On account of its high strength-to-weight properties this alloy is employed in automobile and aircraft engineering constructions. It has been used for front axles, levers, bonnets, connecting rods, and even for chassis frames of automobiles. Its aircraft applications have included girders for airships, aeroplane airscrews, spars, clips, fittings, levers, etc. It is also employed in surgical and orthopaedic work, and for non-magnetic and other instrument parts.

Corrosion of Duralumin

Under certain conditions duralumin is liable to corrode. If kept quite dry it appears to be immune. It is affected only slightly by fresh water and is less prone to attack by acidulated solutions than ordinary steels. On the other hand, alkaline solutions have a more serious effect on duralumin than steel. Usually the products of corrosion occur in spots and in time "pits" are caused on the surface. Unless the surface corrosion is removed by abrasive action some of the "pits"

may deepen or enlarge; in the former method the strength of the metal may be affected.

Duralumin in common with some other aluminium alloys is also liable to *intercrystalline corrosion*. In this case the corrosion commences at the surface and penetrates the metal along the boundaries of the crystals. Unfortunately, from the point of view of inspection it does not produce any appreciable change of appearance of the metal. It has been found that this form of corrosion often commences at isolated points, a typical example* being that shown in Fig. 21. In this case the section was taken from a duralumin sheet which showed indications of corrosion, and it was found that intercrystalline corrosion had started during storage of the original sheet, and during subsequent exposure of the anodically-treated sheet to marine conditions intercrystalline corrosion had continued.

The intercrystalline type of corrosion is invariably accompanied by a marked decrease in the mechanical properties of the metal; in the early stages the elongation values show a marked reduction, and as corrosion proceeds the tensile strength is reduced substantially.

It has also been pointed out by Sutton that the tendency to intercrystalline corrosion appears to be affected by the nature of the heat-treatment and subsequent working of duralumin ; thus, if it is softened by heating to 360° to 380° C. it is more susceptible to intercrystalline attack. Other contributory influences include the temperature of the quenching medium, nature of the surface and deformation.

Duralumin, in common with other aluminium alloys, can be effectively protected against surface corrosion by the methods considered later in this chapter.

Super-duralumin

It has been found possible, by a suitable modification of the composition of duralumin, to obtain alloys which will respond satisfactorily to precipitation heat-treatment, i.e. can be "aged" artificially. Such alloys include M.T.E., B.H.T.A., Super-duralumin, etc. The percentage composition of the latter alloy is as follows: Cu, 4·25; Mn, 0·60; Si, 0·75; Mg, 0·50; Al (the remainder).

If this alloy is quenched in water from 500° C.—which is a somewhat higher temperature than for duralumin—it has a tensile strength, immediately after quenching, of 16·5 tons per sq. in. The alloy then age-hardens progressively until at the end of 72 hours after quenching

* "Light Alloys from the Point of View of Corrosion," H. Sutton, *Journ. Roy. Aeron. Society* (October, 1928).
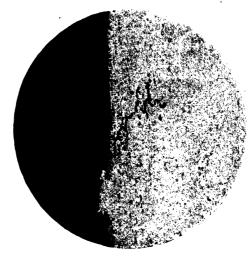
FIG. 21. SECTION OF DURALUMIN SHEET, SHOWING INTERCRYSTALLINE
CORROSION. × 100

FIG. 22. NICKEL-PLATED DURALUMIN, SHOWING INTERCRYSTALLINE
CORROSION. × 100

the tensile strength increases to 26·5 tons per sq. in. This latter value, however, is no better than for duralumin.

If, now, the alloy is subjected to precipitation heat-treatment by exposure for a certain period to temperatures of 100° to 200° C., then it may be "aged" artificially so as to give appreciably better strength properties as illustrated by the results given in Table 30 and the graphs reproduced in Fig. 23.*

Super-duralumin can be produced in the form of rods, sheets,
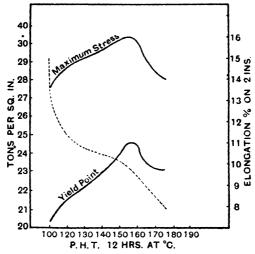
Fig. 23. Effect of Precipitation Heat-treatment on Super-duralumin

TABLE 30

Effect of Precipitation Heat-treatment on the Mechanical Properties of Super-duralumin

Precipitation Heat-treated 12 hours at °C.	Yield Point Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation per cent
100	20·20	27·5	15·0
120	21·50	28·7	12·0
140	23·00	29·5	11·0
155	24·60	30·35	10·0
165	23·30	28·75	9·0
175	23·00	28·0	8·0

* *Ante*, page 58, note.

TABLE 31

COMPOSITIONS, PHYSICAL PROPERTIES AND APPLICATIONS OF R.R. AND Y-ALLOYS

Alloy	Percentage Composition*						Specific Gravity	Coeff. of Linear Expansion × 10⁻⁶	Thermal Conductivity C.G.S.	Applications
	Cu	Ni	Mg	Fe	Ti	Si				
R.R.50	0·8 to 2·0	0·8 to 1·75	0·05 to 0·30	0·8 to 1·40	0·05 to 0·25	1·50 to 2·80	2·75	20°–300° C. 24·0	0°–100° C. . 0·415	Sand and die-castings for cylinder blocks and heads, crankcases and other aircraft and automobile high strength-to-weight parts.
R.R.53	1·5 to 2·5	0·5 to 2·0	1·4 to 1·8	1·1 to 1·5	0·02 to 0·12	2·0 (max.)	2·75	20°–300° C. 23·8	0°–100° C. 0·43	Sand and die-castings for elevated temperatures. I.C. engine pistons, air-cooled cylinder heads.
R.R.56	1·5 to 2·5	0·5 to 1·5	1·2 to 1·8	0·8 to 1·5	0·20 (max.)	1·0 (max.)	2·75	20°–200° C. 22·8	30°–70° C. 0·38	General purpose wrought alloy forgings, stampings, strip, sheet, extrusions. Aircraft engine crankcases, con-rods, cylinders, supercharger rotors, air-screw blades, etc.
R.R.59	1·5 to 3·0	0·5 to 1·5	1·2 to 1·8	1·0 to 1·5	0·20 (max.)	1·3 (max.)	2·75	20°–300° C. 24·0	0°–100° C. 0·428	High-strength wrought alloy for use at elevated temperatures. All kinds of I.C. engine pistons, automobile compression-ignition, motor cycle and aero engine parts.
R.R.53C	0·8 to 2·0	0·5 to 1·5	0·3 to 0·8	0·8 to 1·4	0·30 (max.)	2·0 to 3·0	2·75	20°–200° C. 23·2	0°–100° C. 0·413	Sand and die-castings high-strength ductile alloy. Levers, brackets, C.I. cylinder heads, etc.
Hiduminium Y-alloy	3·5 to 4·5	1·8 to 2·3	1·2 to 1·7	0·6 (max.)	—	0·6 (max.)	2·79	20°–100° C. 22·25	At 200° C. 0·47	Wrought alloy for elevated temperatures superior to R.R.59. I.C. engine cylinder heads and pistons.

* Aluminium, the remainder.

TABLE 32

MECHANICAL PROPERTIES AND HEAT-TREATMENTS OF R.R. AND Y-ALLOYS

Alloy	Condition	Mechanical Test Properties					Heat-treatment
		Tensile Strength Tons per sq. in.	Endurance Limit at 40×10^6 Cycles	Elongation on 2 in. per cent	0·1% Proof Stress Tons per sq. in.	Brinell Hardness	
R.R.50	Cast in D.T.D. sand-lined moulds and heat-treated	11–13* / 13–16†	±4·5* / ±5·8†	2–4* / 4–6†	9–11* / 11–13†	65–75* / 70–80†	Precipitation: 10–16 hr. at 155°–170° C. Quench in hot water or cool in air.
R.R.53	Cast in D.T.D. sand-lined moulds and heat-treated	18–20* / 21–23†	±5·5* / ±6·9†	0·5–1·0* / 0·5–1·5*	— / 19–22†	21–23* / 25–27*	Solution: 2–4 hr. at 520°–535° C. Quench in oil or warm water. Precipitation: 10–20 hr. at 150°–170° C. Quench in water or cool in air.
R.R.56	1¼ in. square forged bar	27–30[2] / 12–15[3]	±10·04[2] / —	10–15[2] / 20–25[3]	21–23[2] / 6– 8[3]	121–138[2] / 45– 55[3]	Solution: 2–6 hr. at 525°–535° C. Quench in hot water. Precipitation: 25 hr. at 165°–180° C. Quench in water or cool in air.
R.R.59	1⅛ in. diam. forged bar	26–28	±10·3	10–15	20–22	124–148	Solution: 2–3 hr. at 520°–530° C. Quench in hot water. Precipitation: 15–20 hr. at 150°–170° C. Quench in water or cool in air.
R.R.53C	Cast in D.T.D. sand-lined moulds (solution treated)	14–15* / 17–19†	±7·2* / ±8·4†	2–3* / 2–3†	9–10* / 10–12†	14–16* / 15–19†	Solution: 2–3 hr. at 520°–525° C. Quench in boiling water. Precipitation: 16–20 hr. at 165°–175° C. Quench in water or cool in air.
Hiduminium Y-alloy	1¼ in. diam. forged bar (fully heat-treated)	24–27	±9·3	15–20	14–17	100–130	Solution: 2–6 hr. at 490°–525° C. Quench in hot water or oil. Ageing at room temperature for 5 days.

Note. R.R.53C alloy. Fully heat-treated gives 19–22 tons per sq. in tensile strength* and 22–24 tons per sq. in.† with corresponding 0·1 per cent proof stress of 18–20* and 19–21† tons per sq. in. respectively.

* Sand cast.   † Die cast.   [2] Solution treated and aged.   [3] Annealed.

strip, tubes, etc.; it is also available in slightly modified composition for fabrication by hot forging and stamping. The forging and hot stamping temperatures lie between 480° and 500° C.

Other Duralumin-derived Alloys

Just as Super-duralumin is an improved alloy derived essentially from duralumin by a modification of composition, so a number of other alloys having special advantages have been discovered as a result of intensive research work. In general such alloys require precipitation heat-treatment as distinct from ordinary age-hardening in order to develop their full strength properties.

Two important groups of light aluminium alloys coming within this category of duralumin modified by the addition of other elements are the "R.R." and "Y" alloys. The proportions of magnesium and silicon in this general class of alloys are changed so that a definite effect is produced upon the instability of the solid solution obtained by solution heat-treatment.

The compositions, physical and mechanical properties, together with the typical applications and heat-treatments of these alloys, are given in Tables 31 and 32.

The R.R. Alloys

These high-strength alloys, the properties, applications and heat-treatments of which are given in Tables 31 and 32, are widely used for aircraft, automobile and other purposes where high strength-to-weight is required and, in the case of the R.R. 59 alloy, for high strength and hardness values at elevated temperatures.

This group of light alloys was originated in the research laboratories of Messrs. Rolls Royce, Ltd., by Hall and Bradbury, and subsequently developed by High Duty Alloys, Ltd. They include the R.R. 50 alloy for normal sand and die-castings; R.R. 53 alloy for sand and die-castings for high-strength properties and use at elevated temperatures; R.R. 53C alloy, a development of the R.R. 53 one, having similar high-strength properties, but with better ductility and resistance to impact and fatigue; R.R. 56 alloy, a general purpose wrought alloy for forgings, stampings, pressings, sheets, extruded sections, strip, tube, etc.; and R.R. 59 alloy for general purposes where high strength is required and with the additional benefits of high strength at elevated temperatures.

All of these alloys are of the heat-treatable class and develop their full strength properties when suitably heat-treated by precipitation or solution treatments.

The R.R. 56 alloy heat-treatment process consists of two opera-
tions, the first being known as the "solution" or "quenching" treat-
ment, in which the material is heated to 525–535° C. for two to six
hours and quenched in warm water at 70° C., cold water or oil. This
operation leaves the material in a medium strength condition and
with relatively good ductility; for example, the maximum stress will
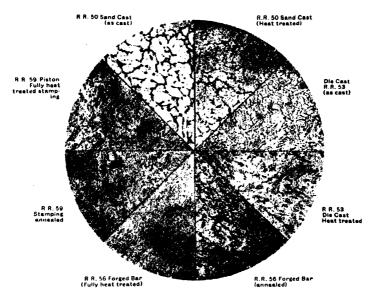
FIG. 24. MICROPHOTOGRAPHS OF THE HIDUMINIUM R.R. ALLOYS
ETCHED WITH 20 PER CENT HNO₃. × 55

be about 22–26 tons per sq. in., and the elongation per cent approxim-
ately 15–20. The second operation consists of the "precipitation" or
"ageing treatment," i.e. heating to 165–180° C. for 20–25 hours (or,
alternatively, 200° C. for two hours), followed by cooling in air or
water.

The fact that it is the second operation which produces the final
high-strength condition has several important advantages. Since the
material after the first quenching is not in a particularly hard condition,
it can easily be cold-formed and can then be hardened by the relatively
simple second operation which, because of the low temperature em-
ployed,* avoids any risk of distortion. Moreover, R.R. 56 alloy does
not "age-harden" to any extent at ordinary room temperature
after the quenching treatment, so that forming operations need

not be carried out immediately after the quenching. Hence manufacturers who do not wish to install the necessary quenching furnace equipment can obtain their material in the quenched form, carry out the necessary manipulation and then "age-harden" it. The elevated "ageing" temperature is also an advantage, because it is of the same order as that used for enamelling and, therefore, this operation
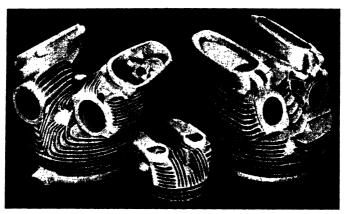
FIG. 25. TYPICAL CYLINDER HEAD CASTINGS IN HIDUMINIUM
(High Duty Alloys, Ltd.)

can be undertaken without any danger of modifying the properties of the alloy.

In order to reduce the alloy to its softest condition it should be annealed at 330–350° C. for from one to four hours.

The forging or hot fabrication of R.R. 56 alloy is carried out at 350° to 400° C. R.R. 56 alloy possesses a similar degree of corrosion resistance to other aluminium alloys, but it can be improved by means of an anodic surface treatment which provides a hard adherent surface film of excellent corrosion resistance; this protective film can be dyed with various finishes and colours. In regard to the tensile strength of R.R.56 alloy at elevated temperatures, the values given in Table 7, on page 16, show that at 20° C. a heat-treated specimen gave a value of 27 tons per sq. in., falling to 10 tons per sq. in. at 350° C. In this respect, whilst superior to most other alloys, it is appreciably less than for Y-alloy (13 tons per sq. in.), whilst its hardness is practically the same.

In connection with the commercial applications of the R.R. 56 alloy, in addition to those given, briefly, in Table 31, this alloy is now used extensively for aircraft frames and wing spars, ultra-light

bicycle frames and wheel rims, motor vehicle bodies, experimental railway coaches, bogies and frames, seat frameworks for various passenger vehicles, crane booms, fire escape towers or booms, etc.; in its extruded bar sections this alloy also has a large variety of industrial uses.

The R.R. 59 alloy belongs to the wrought light metal class and
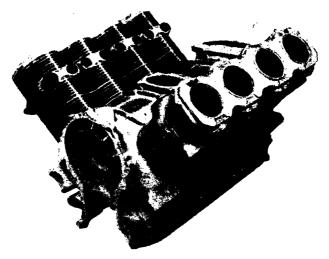
Fig. 26. Cylinder Block and Crankcase Casting in Hiduminium
Alloy
(*High Duty Alloys, Ltd.*)

was evolved for parts subjected in service to high stress at elevated temperatures. It possesses mechanical properties at 'normal working temperatures approaching those of R.R. 56 and has similar hot working properties. These qualities, combined with excellent mechanical properties at elevated temperatures, high thermal conductivity and low friction coefficient, make the alloy an ideal material for use in the manufacture of all types of internal combustion engine pistons. It is regularly employed for all classes of pistons, ranging from the smallest motor cycle to the largest compression ignition engine, and is the standardized material for this purpose in a large proportion of the aircraft engines manufactured in this country.

In regard to the properties of this alloy at elevated temperatures the results of some tests made by the manufacturers are given in Table 33 for test bars forged from 1⅛ in. diameter bar, heat-treated.
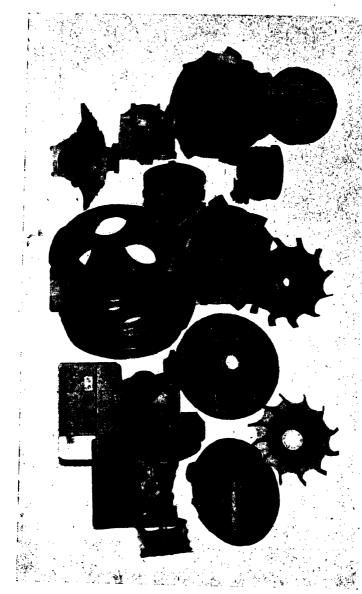
FIG. 27. SOME TYPICAL CASTINGS OF AIRCRAFT ENGINE COMPONENTS MADE IN HIDUMINIUM

(High Duty Alloys, Ltd.)

TABLE 33

PROPERTIES OF R.R. 59 ALLOY AT ELEVATED TEMPERATURES

Temperature	Ultimate Stress Tons per sq. in.	Brinell Hardness at Temperature	Brinell Hardness after Cooling
°C.			
20	28·0	134	—
200	21·5	110	134
250	19·5	87	125
300	13·0	52	90
350	8·0	27	75
400	—	12	70

High-strength Wrought Structural Alloy

A wrought alloy of the Hiduminium group, known as R.R. 77, of somewhat different composition from other strong light alloys, possesses strength-for-weight properties exceeding those of high-tensile steel alloys. The alloy represents the result of prolonged research and, besides its high-strength properties, it possesses excellent ductility, fatigue resistance and electrical and thermal conductivity. Available in various wrought forms it has been used chiefly as extrusions which enable full advantage to be taken of its high-strength properties.

For the hot working and, to a lesser extent, the heat-treatment of this alloy, rather different conditions hold as compared with the better-known Hiduminium alloys.

Parts fabricated from this alloy by special operations evolved for their production possess greater uniformity of properties in different sections and in different directions of flow than it has been possible to obtain in other wrought light alloys.

The percentage composition is as follows: Cu, 1·5 to 3·0; Zn, 4·0 to 6·0; Mg, 2·0 to 4·0; Fe, 0·6 (max.); Si, 0·6 (max); Ni, 1·0 (max.); Ti, 0·3 (max.); Al (remainder).

The heat-treatment is as follows—

Solution treatment: 2 to 3 hours at 455° to 465° C., followed by quenching in water.

Precipitation treatment: 15 to 20 hours at 130° to 140° C., followed by cooling in air.

Test bars forged to $1\frac{1}{8}$ in. diameter and machined to specimen sizes gave a tensile strength of 33 to 38 tons per sq. in. with 16 to 10 per cent elongation on 2 in. The 0·1 per cent proof stress value was 28 to 33 tons per sq. in. The endurance limit at 20×10^6 cycles was

± 12·5 to 13·0 tons per sq. in. The Brinell hardness value was 160 to 180. These results refer to the alloy in the solution-treated and artificially aged condition. When annealed the tensile strength was 12 to 14 tons per sq. in., with 20 to 14 per cent elongation.

Y-Alloy

This important high-strength aluminium alloy was developed at the National Physical Laboratory, Teddington, from the binary copper-
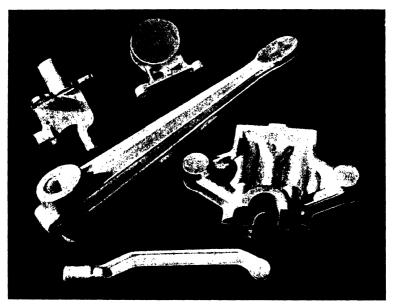
FIG. 28. A GROUP OF HIDUMINIUM R.R. ALLOY STAMPINGS

aluminium alloy by small additions of nickel, magnesium, silicon and iron. A typical percentage composition is as follows: Cu, 4·0; Ni, 2·0; Mg, 1·5; Si, 0·6 (max.); Fe, 0·6 (max.); Al (remainder).

This alloy is heat-treated by quenching in hot water from 510° to 525° C., and either aged at room temperature or by precipitation treatment at 100° to 200° C.

The particular composition alloy mentioned has a minimum tensile strength of 24 tons per sq. in. with a minimum elongation of 15 per cent. The 0·1 per cent proof stress value is 14 tons per sq. in. (minimum).

Y-alloy is generally employed as forgings or parts machined from

bars, but it can be sand and chill cast. In the heat-treated state specimens from sand cast bars have a 0·1 per cent proof stress value of 13 to 14 tons per sq. in., tensile strength of 14 to 15 tons per sq. in. with about 1 per cent elongation on 2 in., and Brinell hardness of 95 to 103. The chill cast alloy gives corresponding values of 14 to 15·5,
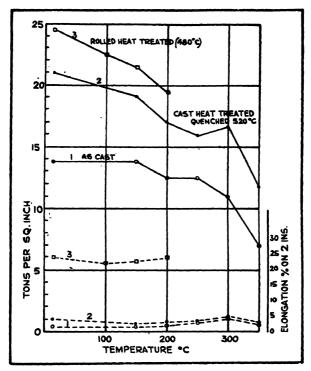
FIG. 29. STRENGTH PROPERTIES OF CAST AND ROLLED Y-ALLOY AT DIFFERENT TEMPERATURES

18 to 20, 2 to 4 and 95 to 105 respectively. Fig. 29 shows the tensile strength and elongation properties of rolled and cast Y-alloy at elevated temperatures; the lower chain-dotted graphs refer to the elongations corresponding to the tensile strength full line curves above.

It should be mentioned that the actual strength properties vary somewhat with the composition and size of casting, but in general do not depart very appreciably from the values given previously.

In regard to the strength of Y-alloy at elevated temperatures it is about the best of known aluminium alloys and for this reason is much used in aircraft engines for cylinder heads and pistons. In the case

of the Bristol air-cooled radial engines the cylinder heads are machined from solid forgings (Fig. 30).

Y-alloy is annealed, in the wrought state, by heating it to 350° to 400° C. and allowing it to cool in the air.

Hot working of this alloy should be carried out at 480° to 500° C.

FIG. 30. (*Left*) FORGED Y-ALLOY, BRISTOL AIRCRAFT ENGINE CYLINDER HEAD. (*Right*) MACHINED HEAD READY FOR SCREWING ON TO STEEL CYLINDER BARREL

Y-alloy is next to the 12 per cent silicon-aluminium alloy in regard to hot-shortness and it possesses good casting qualities. In this connection the following test values are of interest—

TABLE 34

HOT-SHORTNESS OF ALUMINIUM ALLOYS NEAR THEIR MELTING POINTS

Alloy	Temperature Fall in °C. before Energy to Fracture is 10·9 ft.-lb.	Energy in ft.-lb. to Fracture at 5° C. below Melting Point
12 per cent silicon .	3	10·9
Y-alloy . . .	11	4·7
8 per cent copper alloy	24	0·7
2L.5 . . .	45	0·5

Heat-treatment and Age-hardening

The heat-treatment temperature range of Y-alloy is 500°–520° C.; this is higher than for duralumin.

It has been found that the muffle furnace is the best medium for

heat-treating Y-alloy. The period of treatment at 500°–520° C. required to bring about solution of age-hardening constituents depends on the fineness of grain and distribution of constituents. For chill-cast bars, 1 in. diameter, about 6 hours is required. For coarser grain material a longer period becomes necessary, whilst for large sand-castings 24 hours or more may be required. In all cases the period of
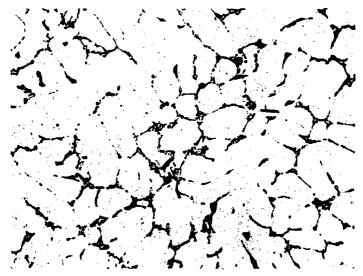
FIG. 31. Y-ALLOY, CHILL CAST 1 IN. DIAMETER BAR, AS CAST

treatment at 500°–520° C. (solution treatment) must be regulated in relation to the micro-structure. Treatment at the temperature 500°–520° C. is followed by quenching in boiling water. After quenching, *age-hardening* at room temperature is substantially complete in 5 days.

Age-hardening can be accelerated by retaining the alloy immersed in the water at boiling temperature after quenching. Under these conditions age-hardening is substantially complete in from $\frac{1}{2}$ hour for the wrought to 2 hours for the cast alloy.

By subjecting normally heat-treated material, cast or wrought, to temperatures between 150°–250° C. the tensile strength and hardness are substantially increased, but the ductility is diminished. Above 250° C. permanent softening results.

Structure of Y-Alloy

The microstructure differs somewhat from that of duralumin. The copper-aluminium compound $CuAl_2$ does not exist in Y-alloy,
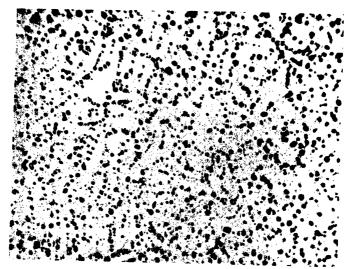
FIG. 32. Y-ALLOY, CHILL CAST 1 IN. DIAMETER BAR
HEAT-TREATED AT 520° C.

FIG. 33. Y-ALLOY, CHILL CAST 1 IN. DIAMETER BAR
HEAT-TREATED AT 520° C.

but instead there is a more complex compound of copper, with nickel and aluminium, together with the nickel-aluminium compound $NiAl_3$.

The structure* of Y-alloy in the chill cast state, illustrated in Figs. 31, 32, and 33, shows an almost complete network of the various constituents in a ground mass of substantially pure aluminium. Heat-treatment properly carried out brings about changes in these constituents together with partial solution in the aluminium, and as a result the continuity of the network is broken and free constituents become rounded in outline and "balled-up." Fig. 33 shows the

FIG. 34. Y-ALLOY CYLINDER HEAD OF BRISTOL AIRCRAFT ENGINE, SHOWING BRONZE VALVE SEATINGS

structure of the heat-treated cast alloy under higher power. Three constituents are to be seen—the *white* aluminium matrix, the *half-tone* copper-nickel-aluminium compound, and the *dark* compound $NiAl_3$.

Bronze Inserts in Y-Alloy Cylinder Heads

Owing to the fact that the expansion coefficient of Y-alloy, in common with other high-strength aluminium alloys, is nearly 3 times that of steel it is not satisfactory to employ ordinary alloy steels for valve seating and sparking plug ring inserts in cylinder heads of such alloys. These inserts are therefore made in nickel-aluminium-bronze which has a similar expansion coefficient combined with satisfactory hardness and resistance to scaling effects.

A later alternative material for these inserts is an *austenitic steel* of the nickel-manganese-chrome steel class, having about the same

* "Aluminium Alloy 'Y,'" Archbutt, *The Nickel Bulletin*, No. 7. Vol. **3** (July, 1930).
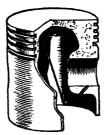
expansion coefficient as Y-alloy. These cold insert rings are inserted into the heated cylinder head so as to produce a shrinkage or interference fit.

Petrol Engine Castings

Aluminium alloys, on account of their high strength-to-weight properties, excellent thermal conductivity, and the ease with which

A simple "pot-type" alloy piston for low output engines

A slit-skirt design with reinforced gudgeon pin bosses

One of the Covmo range, with cutaway skirt and ribbing

Inclined internal struts are a B.H.B. characteristic

The Aerolite piston with stiffening flutes and webs

The Invar-Strut controlled-clearance piston: a neat design

FIG. 35. EXAMPLES OF ALUMINIUM ALLOY PISTONS

(Courtesy British Aluminium Co., Ltd.)

most of the modern ones can be sand and die-cast, are widely used for parts such as cylinder blocks and heads, pistons, and crankcases.

As it is necessary to provide sufficient strength at the usual working temperature, only those alloys having suitable strength properties at these temperatures are satisfactory. Such alloys include the copper-aluminium ones, of which 3L.11 with 7 per cent copper and a tensile strength of about 9 tons per sq. in. is an example; R.R. casting alloys previously described and a number of proprietary alloys, such as

Alpax, Ceralumin, Wilmil, B.A. and N.A. casting alloys, and those to B.S.I. and D.T.D. specifications.

For pistons the usual alloys are Y-alloys, R.R.53 and R.R.59.

Typical examples of aluminium alloy pistons are given in Fig. 35.

Fig. 36 is a part-sectional view of the cylinder head of the Wright
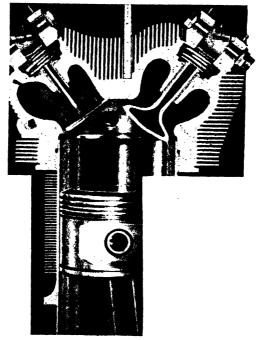
FIG. 36. WRIGHT "CYCLONE" ALUMINIUM ALLOY CYLINDER HEAD

"Cyclone" aircraft engine. This has a sand-cast aluminium alloy head with nickel-aluminium-bronze valve inlet and stainless steel exhaust seating rings shrunk into place. The cylinder barrel is of a Nitralloy steel.

A good example of an intricate large aluminium alloy casting is that of the Napier "Culverin" twelve-cylinder (double-six) aircraft engine shown in Fig. 37.

Two typical examples* of automobile engine crankcases are those shown in Figs. 38 and 39, whilst a cleanly-cast crankcase sump is illustrated in Fig. 40.

* Courtesy British Aluminium Co., Ltd.

Corrosion of Aluminium Alloys

All of the light aluminium alloys are subject to corrosion under atmospheric and salt water conditions, but some are much more resistant to these corrosive influences than others. They are, however,
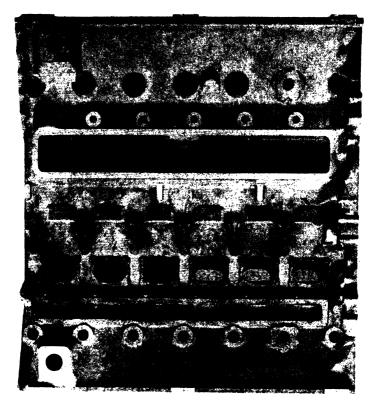
FIG. 37. ALUMINIUM ALLOY CYLINDER BLOCK AND CRANKCASE UNIT FOR NAPIER TWELVE-CYLINDER "CULVERIN" AIRCRAFT ENGINE

(*High Duty Alloys, Ltd.*)

no worse than ordinary steels in this respect. Pure aluminium is more resistant in air than its alloys, the surface of the metal becoming coated with a thin layer of practically colourless oxide which acts as a protective medium against further atmospheric corrosion. It is on this account that light alloy sheets are frequently treated so as to give a thin layer of pure aluminium (as in Alclad) or of aluminium oxide (as in the anodizing process).
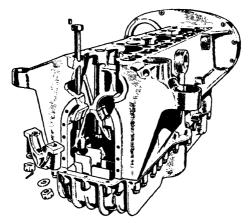
FIG. 38. A COMPLICATED CASTING IN ALUMINIUM ALLOY (ALVIS ENGINE CRANKCASE)
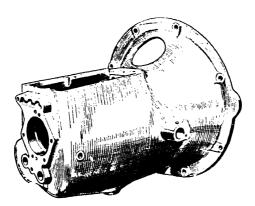
FIG. 39. COMBINED CAR ENGINE CRANKCASE AND CLUTCH HOUSING IN ALUMINIUM ALLOY
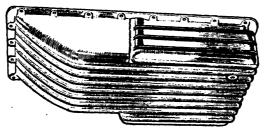
FIG. 40. RIBBED ALUMINIUM ALLOY CRANKCASE OIL SUMP

The tendency of duralumin and certain other alloys to *intercrystalline corrosion* has already been referred to. It may here be added that alloys which have been precipitated are more susceptible to this form of corrosion. In regard to the general *effect of sea-water* or spray upon aluminium and its alloys the chlorides appear to be the chief cause of corrosion. The areas affected are usually localized and deep pits occur.

At these places the chlorine ions coming into contact with the aluminium form the chloride salt of this metal. This salt, in contact with water, hydrolyses, forming aluminium hydroxide and hydrochloric acid. The latter reacts with further quantities of aluminium so that a cycle of reactions is maintained; in this manner a small amount of chloride can affect detrimentally a relatively large area of aluminium.

Another important factor is that of *differential aeration*; the effect of restricted access of oxygen to a particular area of metal is to concentrate corrosion in that area.

Where an aluminium alloy is in *metallic contact* with another metal, such as steel or brass, an electrolytical action occurs in the presence of moisture and corrosion effects follow. In this connection aluminium is electropositive to other common metals, with the exception of magnesium.

In some cases corrosion, commencing at the junction of the two metals, has been found to spread internally in aluminium sheet, causing long blisters to radiate from the contact area. *One method of obviating or greatly reducing such corrosion is to zinc coat* all copper, brass, bronze, and steel articles in contact with aluminium or its alloys, since zinc and aluminium are very close together in the electrochemical series, shown in Table 35.

TABLE 35

ELECTROCHEMICAL SERIES OF METALS

1. Caesium	12. Manganese	23. Arsenic
2. Rubidium	13. Zinc	24. Copper
3. Potassium	14. Cadmium	25. Mercury
4. Sodium	15. Iron	26. Silver
5. Lithium	16. Cobalt	27. Palladium
6. Barium	17. Nickel	28. Platinum
7. Strontium	18. Tin	29. Gold
8. Calcium	19. Lead	30. Iridium
9. Magnesium	20. (Hydrogen)	31. Rhodium
10. Aluminium	21. Antimony	32. Osmium
11. Chromium	22. Bismuth	

In this table each metal is electropositive to any other metal having the greater number before it, or below the metal in the table.

Aluminium and its alloys are attacked by *alkaline solutions,* e.g. caustic soda, caustic potash and sodium carbonate.

Nature of Alloy and Corrosion Resistance

As stated previously, some of the light alloys of aluminium are more resistant than others to corrosive influences. The wrought alloys corrode to a lesser extent than steels with the exception of the stainless class.

It has been established that none of the alloys which owe their hardening to the presence of copper and magnesium, with silicon also, and submitted to a hardening treatment involving the breakdown of the quenched solid solution is very resistant to corrosion. On the other hand, in the solution heat-treated condition such alloys have a resistance to corrosion at least as good as that of pure aluminium.

Typical corrosion-resisting alloys in this class are duralumin "H" and the clad metal, known as "Duralplat." These alloys contain magnesium and silicon, whilst the surface layer of the latter contains manganese as well. It has also been shown* that if an alloy contains a solid solution which is not stable the resistance to corrosion is lessened considerably. Thus, the alloys in which the solid solution is broken down by precipitation heat-treatment above 125° C. have a considerably lower corrosion resistance than those alloys in which the solid solution is unstable at room temperatures and which age completely at that temperature. The corrosion resistance of duralumin, whilst being inferior to pure aluminium, is much greater than that possessed by alloys which have been artificially aged by precipitation at temperatures above 125° C. In this connection those alloys of the "R.R." group are inferior to duralumin.

It has been suggested as a result of much research that *the resistance to corrosion of alloys* which have been submitted to artificial ageing *is very nearly inversely proportional to the proof stress of the fully heat-treated material.*

Some Corrosion-resistant Alloys

In view of these facts it has become necessary to investigate other aluminium alloys with a view to obtaining a satisfactory combination of strength and corrosion resistance; as a result of such researches certain promising alloys have been discovered and these are now available commercially.

Notable among these alloys is the *aluminium-magnesium* one having 7 per cent of magnesium and 0·25 per cent of manganese. This

Ante, page 61, note.

is a non-heat-treatable alloy having a high resistance to corrosion by marine atmospheres and salt waters. This alloy is available in all the forms of duralumin and is also used for rivets. It is known, commercially, as MG.7 alloy.

Another corrosion-resistant alloy of the same series has $2\frac{1}{2}$ per cent of magnesium and 0·25 per cent of manganese.*

The introduction of *chromium* into some of the aluminium-magnesium alloys has been found to improve still further their corrosion resistance.

Another alloy of the aluminium-magnesium series is that known as *Birmabright*. This contains 3·5 per cent of magnesium and is used for sheet metal parts of boats, e.g. the outer plates of small boats, motor boats, etc.

A low-strength alloy of the non-heat-treatable class possessing practically the corrosion resistance qualities of pure aluminium is *Hiduminium 15*, containing 1·0 to 1·5 per cent manganese, the remainder being aluminium. It is supplied in soft, half-hard and hard sheets and in the two former tempers has very good cold-working qualities. It has corresponding tensile strengths of 6·5 to 7·5, 8 to 11, and 12 to 16 tons per sq. in. respectively. In the soft state the elongation is 25 to 40 per cent; in the hard state it is 3 to 6 per cent.

For medium-strength properties, *Hiduminium 33* has excellent resistance to corrosion. It contains 2·6 to 3·3 per cent magnesium, 1·0 to 1·5 per cent manganese and 0·2 per cent titanium. In the soft, half-hard and hard conditions the tensile strengths are 15 to 17, 20 to 22 and 22 to 26 tons per sq. in. respectively. The corresponding elongations are 15 to 25, 5 to 8 and 3 to 5 per cent, on 2 in. The average Brinell hardnesses are 50, 75 and 100, respectively.

A stronger corrosion-resistant alloy is Hiduminium 35 which in the hard state—obtained by cold-working—is from 26 to 30 tons per sq. in. with 5 to 2 per cent elongation, and a Brinell hardness of 100 to 120.

There are now several other Hiduminium and proprietary makes of aluminium alloys for cast and wrought conditions possessing good resistance to corrosion.

Oxide-coated Aluminium Pistons

The ordinary aluminium alloy pistons used in automobile engines are more prone to wear and "scuffing" action than the earlier cast-iron ones which they replaced. In order to overcome this drawback and to produce pistons which are practically immune from wear, the

* See also page 44.

alloy aluminium piston is now given a surface coating which is very hard and can neither be scratched nor scuffed.

The pistons are immersed in a tank containing a solution of sulphuric acid. This solution is maintained at a temperature of 70° F. While in the solution, the piston, carried on a conveyor, is the anode for the coating operation. It emerges from the tank with an aluminium oxide surface approximately 0·00025 in. thick; aluminium oxide is one of the hardest substances known to metallurgy.

In the electro-coating process, the piston rings and piston pin hole are treated as well as the piston itself. Once the unit has received its coating of aluminium oxide, further work cannot be performed as the surface is too hard for any tool. The coating is done in a cold solution, and there is consequently no distortion of the piston during the process.

" Clad " Aluminium Alloys

These alloys, which are in the sheet form, are protected against corrosion by having a superficial layer of pure aluminium on each side; as stated previously, aluminium itself has very good corrosion resistance properties. Typical examples of commercial "clad" lloys are Alclad* and Aldural.†

Alclad consists of a core of strong heat-treated aluminium alloy comprising approximately 90 per cent of the thickness, leaving about 5 per cent on each side of pure aluminium. There are three distinct zones, namely, the pure aluminium one, the junction between the aluminium and base metal, and the base metal itself.

The junction of the base metal and coating represents an alloying of the two as shown by the photomicrograph of a typical sheet metal section shown in Fig. 41. The aluminium coating not only resists corrosion and prevents contact of the corroding media with the core, but since pure aluminium has a higher solution potential than the core alloy, in the presence of moisture the latter will be preserved at the expense of a small amount of the coating.

This electrolytic protection extends to the cut edges of the sheet and also to rivets and bolts of aluminium alloy or to deep scratches or abrasions. Cases have been known of flying boats in which, through constant beaching, the greater part of the aluminium coating has been worn away, yet the duralumin core still remained unaffected by the salt water.

* Northern Aluminium Co. Ltd.
† James Booth & Co. Ltd.

In the workshop, rather more care than usual is perhaps needed in handling Alclad to prevent scratching and damaging the soft outer coat, but in view of the foregoing remarks it will be appreciated that scratches do not seriously affect the corrosion resistance. In bending and flanging operations which involve the stretching and compression of the outer fibres of the material the ductile coating on this material
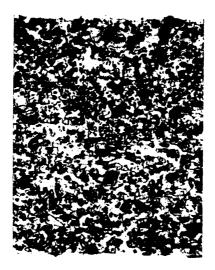
FIG. 41. PHOTOMICROGRAPH OF ALCLAD SHEET, 16 S.W.G.
× 40

enables sheet to be formed over a sharper radius than is usually possible with uncoated sheet of the same gauge.

There may be several methods used in the production of Alclad, but essentially the process consists of rolling on to the two outer surfaces of an ingot of strong alloy two plates of pure aluminium. The plates may be affixed during the casting of the ingot or during the hot rolling process but in either case the main welding of the two materials occurs during hot rolling and is consolidated in the subsequent cold rolling and thermal treatments.

The core alloy used is frequently of the duralumin type as in the British Standard Specification L.38 but there are other Alclad alloys with core materials of either the single or double heat-treated types. More recently there has been produced a "clad" alloy known as Alclad NA.23S conforming to specification D.T.D.390 which was designed especially to combine the corrosion resistance of Alclad with

the strength of uncoated duralumin (B.S.S.5L.3) yet to possess the ductility of B.S.S.L.38 sheet and strip.

Aldural is an aluminium-clad duralumin alloy sheet with a thickness of about 5 per cent of pure aluminium on either surface. The resultant product is only slightly inferior in mechanical strength properties to the core alloy. As with Alclad the aluminium is cathodic to the duralumin and therefore confers electrolytic protection on the latter, so that there is no preferential corrosion at cut edges or at holes. Moreover, when this clad metal is riveted with duralumin rivets the

FIG. 42. SHOWING JUNCTION OF THE PURE ALUMINIUM COATING WITH CORE ALLOY, IN ALCLAD × 100

heads of the latter are protected, electrolytically, by the aluminium surface.

Aldural conforms to the Air Ministry specification 2L.38, while the D.T.D. 390 specification covers the "Aldural G" alloy; this has a stronger core than the former alloy sheet. The following are the minimum specified mechanical properties.

TABLE 36

PROPERTIES OF ALDURAL CLAD ALLOYS

Aldural Specification	0·1% Proof Stress Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation per cent
2L.38 . .	13·5	24·0	15·0
D.T.D.390 . .	15·0	25·0	15·0

In regard to heat-treatment the composite alloy is dealt with in exactly the same manner as duralumin.

Duralplat is an aluminium alloy sheet of the duralumin class coated on either side with a corrosion-resisting alloy containing magnesium, manganese and silicon. It has a proof stress of 17 to 18 tons

per sq. in., tensile strength of 26 to 27 tons per sq. in. and elongation of about 17 to 18 per cent. After 150 days' exposure to a salt water spray the proof stress is diminished only by about 5 per cent.

Protection of Aluminium Alloys

When aluminium alloys are used in places where they become exposed to atmospheric and sea air and other corrosive influences, it is necessary—as in the parallel instance of steel—to protect the surfaces either by suitable coatings of organic materials or by chemical methods, such as anodizing. The protective media, if in the form of paints, enamels, varnishes, etc., must be of a neutral character in relation to the alloy, so that no acid or alkaline action can occur. The 'cellulose and synthetic resin varnishes and paints afford good protective value.

As the surfaces of many light alloy parts are usually smooth they do not give good adherent media for paints and varnishes, so that it is an advantage to sand-blast, frost or otherwise obtain a matt surface for better adherence of the protective materials.

The M.B.V. Process. The M.B.V. process of surface preparation is to immerse the aluminium alloy articles in a boiling solution consisting of 5 per cent sodium carbonate plus 1·5 per cent sodium chromate for 3 minutes, followed by washing in water and drying. The effect of this treatment is to give a thin grey film which is an excellent key for paint or varnish. The surfaces to be protected must be entirely free from grease. In the application of the protective material a spray gun is recommended.

Except, perhaps, in the case of non-heat-treatable alloys stove-enamelling or baking processes for certain of the synthetic resin paints and varnishes should not be used, since the higher temperatures will usually affect the heat-treatment results previously obtained. Cold synthetic resins are now available which give satisfactory results. Low temperature stove-finishing synthetic lacquers can be used in certain instances and in this respect the stoving temperatures are about 120° to 150° C.

In connection with the general use of paints, enamels, lacquers, etc., the principal objection to these for light alloy protection is that they have a relatively low resistance to surface abrasion, scratching, etc., so that for parts liable to rough usage the metal below may become exposed, locally, to outside corrosive influences.

Plating Methods. Aluminium and its alloys are difficult to nickel or chromium plate, but methods now available have been applied successfully to certain articles, including domestic aluminium ware. When parts are nickel-plated it is sometimes necessary to heat them to about

250° C. in order to produce an intermediate layer of alloy rich in the plating metal. When chromium is employed, it should not be applied to the aluminium alloy direct—since fine hair cracks occur—but over a basic nickel coating.

Metal Spraying Method. Another method of protecting aluminium alloys is by the *Schoop metal spraying process* in which a ribbon of the protective metal; e.g. zinc, lead or aluminium is fed into a special design of spray gun where the metal is melted and sprayed on to the alloy by compressed air. This method has been employed to coat alloy sheets with pure aluminium as in the Alclad process.

The Anodizing Method. The anodizing method previously referred to is now more widely employed than most others. It was originated by Dr. C. D. Bengough and J. M. Stuart in 1921–24,* and depends upon a chemical method of obtaining a protective film of aluminium oxide or hydroxide by making the metal the anode in a bath of dilute chromic acid and using a carbon cathode (subsequently a stainless steel cathode was used with success). The process is suitable only for aluminium and aluminium alloys, so that the anodic film is composed almost entirely of aluminium oxide in a glassy adherent form.

The anodic oxidation of aluminium has a marked influence on bending tests for thin sheets, increasing the permissible radius of the bends in both longitudinal and transverse directions, but without substantially altering the tensile strength of the material.

The anodic process is widely adopted for the protection of aluminium used in aircraft construction. It is also used to produce finishes of pleasing colours. A further use is to increase the surface hardness of aluminium pistons; it gives a thicker coating than the first process described on page 85.

The electrolyte consists of 3 per cent chromic acid solution and is worked at a temperature of 40° C. It is contained in a plain iron tank heated by steam coils, gas burners or electric elements. Water coils have also to be provided to maintain the temperature at the correct value. Agitation is desirable to prevent local overheating of the electrolyte.

Aluminium sheet requires a current density of from 3 to 3·6 amps. per sq. ft., but the maximum current density may vary considerably, according to the composition of the articles treated.

As in all electrolytic processes the aluminium must be chemically clean before the anodic oxidation is begun. It is cleaned by simple

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* A full account is given in publication on "The Anodic Oxidation of Aluminium and Its Alloys as a Protection against Corrosion," H.M. Stationery Office, London (1s. 3d.).

immersion in a hot solution of "Zonax" metal cleaner of a strength of 8 oz. per gallon, contained in a plain iron tank. Should any heavy polishing composition or grease be present, the pieces should be swabbed with a cotton mop. They are then well swilled and put into the anodic solution.

They must be suspended by aluminium wire or duralumin rod. Should any other metal be put in the solution anodizing will not occur as the foreign metals will take all the current.

The voltage across thè bath terminals is raised gradually from 0 to 40 in about 15 minutes, maintained at 40 for 35 minutes, raised to 50 in a period of 5 minutes and maintained at this value for a further 5 minutes.

Acid Anodizing Method. Another method, known as the acid anodizing process, is sometimes employed and utilizes sulphuric acid solution as the electrolyte with a lead cathode; it is similar to the process given on page 85. The solution is contained in a lead-lined container with means for getting rid of the hydrogen formed. The voltage across the bath terminals is about 15 and the current density 15 amps. per sq. ft. The method gives a very hard skin and for this reason is sometimes used for anodic coating of aluminium pistons. Anodized alloys can readily be coloured by means of aniline dyes immediately after the oxidation of the metal. The dyes or pigments used should be fast to light and weather conditions.

Temporary Protective Materials

Aluminium alloys in storage are usually protected by means of preservatives employing solutions of wool fat or anhydrous lanolin. Even after anodizing it is advantageous to protect stored parts in this manner. If zinc or barium chromate is added to lanolin an appreciably greater measure of protection is secured. An important advance in aircraft component protection* is that of resin or wax-hardened lanolin preparations containing a pigment. The solvent may consist of equal parts of white spirit and naphtha to which is added about 40 per cent of 60–40 mixture of lanolin and resin or wax-hardening medium. A special zinc chromate pigment together with a small proportion of kaolin is introduced to prevent caking. This protective medium can be applied by spraying or brushing. It has the advantages, therefore, of ease of application and lightness, since the weight of resin-hardened lanolin film is only about 0·6 oz. per sq. yd. In the case of a large flying boat if this protective medium is used

* "Some Corrosion Problems Relating to Modern Aircraft," A. J. Sidery and J. W. W. Willstrop, *Journ. Roy. Aeron. Soc.*, 19th January, 1939.

instead of pigmented varnish or enamel the weight of the coating can be reduced from about 400 lb. to 120 lb.

Corrosion of Riveted Joints

Experience has indicated that corrosion occurs at riveted joints in the aluminium alloy plating of flying boat hulls and floats. If, however, aluminium clad sheet, such as Alclad or Aldur, is employed in conjunction with anodized duralumin rivets this difficulty may be overcome satisfactorily.

Aluminium Sheet Metal Work

Aluminium and many of its alloys are admirably adapted to sheet metal work on account of their lightness, the ease with which they can be worked, and their low cost; with the exception of sheet-iron, aluminium is probably the cheapest metal on the market.

It can be obtained in a variety of grades, from dead-soft to hard-rolled, and each grade can be chosen so as to suit the requirement of the object to be made. Sheets may be finished with any degree of polish or frosting, and the finish is more or less permanent.

The applications of sheet aluminium include aircraft engine cowling, fairing, panels, and general body parts; automobile body work; railway coach work; lamps (spinnings); pressings, and numerous other purposes.

The following brief notes refer to some of the commercial aluminium sheet metal fabrication processes.*

(1) *Blanking.* For moderate numbers of blanks cast alloy iron dies are used, with or without a hardened steel insert. For limited numbers of blanks mild steel dies are used.

The clearance between the punch and die is important if blanks with smooth edges are required. As a general rule the difference between the diameters of the punch and die should lie between 10 per cent and 16 per cent of the thickness of the aluminium sheet. The use of a lubricant, such as paraffin, is recommended to prolong the life of the die and give clean blanks.

(2) *Pressing and Drawing.* The dies used are generally of hardened tool or chrome steel and are given a high surface finish in order to prevent clinging of the aluminium. A slightly tapered punch is recommended to facilitate stripping.

An important factor in punch and die design is the relation between the radii of the edges of the tools and the metal sheet thickness; as

* Recommended by British Aluminium Co.

a general rule the punch radius is made equal to between 6 and 10 times the metal thickness.

The clearance between the punch and die should be at least 5 per cent greater than the thickness of the metal. For the final operation of a series, dies are sometimes made with a clearance of less than the thickness of the metal to give a smooth hard surface to the pressing, but with a slight reduction in thickness.

For pressings and deep drawing it is important to employ a suitable lubricant. For shallow drawing, stamping and blanking, paraffin is used, but for deep drawing and pressings vaseline or lard oil should be employed.

In regard to the number of draws or passes, the reduction in diameter is governed by the strength and thickness of the metal. As a rule it may be assumed that for a single operation draw a reduction up to 50 per cent of the blank diameter can be obtained. For multiple operations a first reduction draw of 48 per cent can be followed by subsequent reductions of 30 per cent, 25 per cent and 20 per cent, but the actual values will depend upon the nature of the work, the temper of the metal and amount of ironing given to it.

Pure aluminium of soft temper is most suitable for heavy single operation draws and dome-shaped pressings. For multiple operations half-hard or even hard temper is preferable, since after the first operations such tempers will often withstand more severe reductions than soft temper; on the other hand, hard temper aluminium is more liable to wrinkling and therefore requires greater pressure on the pressing ring. Intermediate annealing is seldom necessary, but if final ductility is required for, say, a final beading operation, material of hard temper is advised in order to avoid excessive grain growth in the least worked portions at the base of the cup.

(3) *Spinning.* Where a small number of symmetrical sheet metal parts is required, spinning is much cheaper than pressing, owing to the relatively high cost of the dies. Spinning is carried out on the soft-temper metal in a simple kind of lathe using a series of hand tools to deform the circular blank as the latter is rotated by the lathe chuck. Usually, the metal blank is held tightly against the rotating former or chuck by means of a wooden centre-piece carried by the tailstock of the lathe and the necessary pressure for forming is applied by a lever motion of the tool acting against a pin on the lathe bed rest.

With aluminium the speed of rotation should be high, a peripheral speed of about 3000 ft. per min. being used. Thus for work of 3 in. to 6 in. diameter the chuck speed of rotation would be about 2000 r.p.m.; for work of 15 in. to 20 in. diameter, 500 r.p.m.; and so on.

In regard to the size of work that can be spun by hand, it is not unusual for blanks up to 6 ft. diameter to be used for spinnings. The chuck is usually made of beech for short runs, but boxwood or lignum vitae chucks have a much longer useful life. For permanent chucks, iron or aluminium alloy would be used. In many cases split chucks are used so that the work can readily be removed when the spinning operation is completed.

Before and during the spinning process the blanks should be lubricated with vaseline or lard oil applied with a rag or brush.

Machining of Aluminium Alloys

Pure aluminium, on account of its softness, requires care in machining, owing to the tendency of the tool to tear the metal. For this
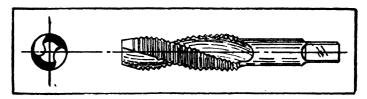
FIG. 43. SPECIAL SPIRAL-FLUTED TAP FOR ALUMINIUM ALLOYS

reason the cutting angles must be correctly selected and the tool edges kept sharp, preferably by oil-stoning after grinding. For many purposes diamond-pointed tools are used in production work for turning aluminium alloys. The machining speeds of light aluminium alloys may be high, thus reducing machining times and therefore costs.

In regard to machining speeds these depend to some extent upon the nature of the process and in this connection the following notes, referring to the recommended practice of the British Aluminium Company, are given.

Turning. The tool should always be finished with the keenest possible edge and any grinding marks should be removed by an oilstone. The top surface of the tool should offer as little resistance as possible to the turnings, and should be ground to a very smooth finish.

It should have a front clearance of about 10°, a top rake ranging from 40° for softer alloys to 30° for harder ones and a cutting edge angle of 35 to 50°. Provided that the work is of a rigid nature as much as $\frac{1}{8}$ to $\frac{5}{32}$ in. sometimes may be taken off in one roughing cut when running at a speed of from 500 to 700 ft. per minute. A lubricant should be used for heavy cutting of this nature although lighter roughing cuts often are done dry. A speed of 600 to 800 ft. per minute

may be used for finishing cuts when using ordinary carbon steel tools. With tools of high-speed steel, the speed may be even higher. The attainment of a good surface depends upon a very light cut and a slow feed. A lubricant always should be used for finishing cuts, and

(A)   (B)

(C)   (D)
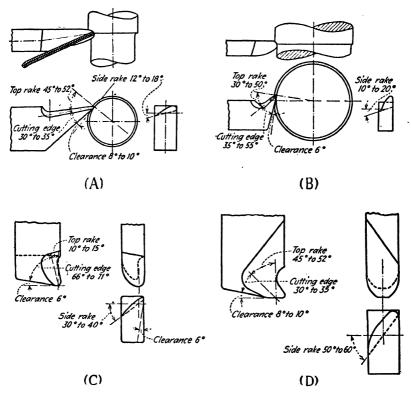
FIG. 44. TOOLS FOR MACHINING ALUMINIUM ALLOYS
A—Turning tool for small diameter work.
B—Turning tool for large diameters.
C—Side-cutting planing tool.
D—Planing and shaping finishing tool
(*Northern Aluminium Co., Ltd.*)

a mixture of paraffin oil and lard oil, or rape oil, in equal proportions gives good results with most aluminium alloys.

The lubricant should be used under pressure, and be so fed that it tends to clear away the turnings from the work.

It is important to remember that the coefficient of expansion of light aluminium alloys is high, and it is essential that the work be cooled before measuring and finishing to accurate dimensions.

Screw Cutting and Tapping. Screw threads may be cut in the usual way, first with a single pointed tool and then with a hand chaser for finishing. For good work it is essential to use a liberal amount of lubricant. Paraffin oil is recommended. Fluted taps are preferable for tapping holes in aluminium but with care it is possible to obtain good results with ordinary taps, provided that the initial hole is of the correct diameter. The best diameter is found by trial. With soft aluminium the hole should be larger than with harder aluminium castings, for example, because the tap has a pressing effect in addition to the cutting action, and allowance must be made for this.

For tapping, bees-wax or tallow is used for lubrication.

In repetition work, threads sometimes are formed by a process known as "thread rolling." Hardened rolls having threads cut upon them are pressed into the aluminium, raising a corresponding thread by squeezing the metal. This process can be applied to screws up to 2 in. or more in diameter.

Milling. This is a process much used on aluminium castings and one to which aluminium particularly lends itself. The only special feature is the use of tools in which the teeth are set further apart than usual to avoid clogging of the metal particles. Where a bright finish is required, paraffin should be used as the lubricant. Ordinarily, however, when a mirror finish is not desired, milling is done dry, and high speeds are used.

For milling "Y" and "R.R." alloys cutters having a face angle of $17\frac{1}{2}°$ and a cutting angle of $15°$ are recommended. A typical cutter of $4\frac{1}{2}$ in. diameter, with 10 teeth, is shown in Fig. 45.* The milling speed for this cutter is 300 r.p.m. with a feed of 0·006 in., both for roughing and finishing; for the latter operation only a very light cut is taken.

Drilling. The drill ordinarily used for aluminium is the standard twist type, although the use of flat drills is sometimes advocated. For "Y" and "R.R." alloys a drill point angle of $90°$ instead of the usual $118°$ is recommended. The cutting speed is 200 ft. per min. with an average feed of 0·005 in.

The same precautions regarding keen edges apply to drills as to turning tools. Aluminium should be drilled at a high speed but with only a moderate feed. The best peripheral speed is from 150 ft. to 200 ft. per min., which means about 600 r.p.m. for a drill 1 in. in diameter. With a 1-in. drill the feed should be about 0·005 in. per revolution, while for a $\frac{1}{2}$-in. drill the corresponding figure is 0·003 in. Paraffin is an excellent lubricant.

* Courtesy, Bureau of Information on Nickel.

Grinding. Both rough and precision grinding are extensively practised on aluminium. There is a large variety of grinding wheels available, and it is recommended that manufacturers of the wheels be consulted as to the best grades to use for any particular purpose. Usually, the harder the work the softer the wheel employed, but with aluminium a soft or medium-soft wheel should not be used owing to the tendency for the metal to clog the wheel. High speeds up to 10,000 ft. per min. should be employed for wheels of the carborundum type, and about 6,000 ft. per min. for wheels with shellac or other soft binders. Rough grinding wheels may be kept from clogging by rubbing
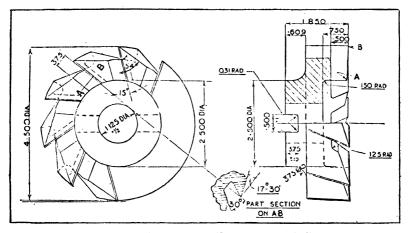
FIG. 45. MILLING CUTTER FOR Y-ALLOY AND R.R. ALLOYS

paraffin wax upon them. This prevents the adhesion of the metal particles without impairing the cutting ability of the wheel.

Filing. For filing aluminium single cut files always should be employed, as those of the double cut type rapidly clog and become useless. A quick method of cleaning clogged files is to dip them in strong caustic soda solution for a moment, after which the metal particles can be wiped off easily. A wash in cold water and a drying in sawdust should follow this treatment or rusting is likely to take place.

Sawing. A band-saw is excellent for such work as cutting off runners and risers from castings. The teeth should be large and the speed about 600 ft. per min. Band-saws should be lubricated with oil or, preferably, tallow.

Reaming. For reaming the harder alloys, such as "Y" and "R.R." ones, the reamers used are made to precision diameter for a length of

$\frac{1}{4}$ in. only, the remaining length being slightly below this diameter. The speed of reaming varies from 60 r.p.m. for a 3-in. diameter to 100 r.p.m. for one of $1\frac{3}{4}$ in. The recommended lubricant is paraffin.

Polishing. Aluminium is capable of taking, and retaining, a high polish, equal to that of silver, without any special arrangements being required.

It is advisable to avoid the use of coarse abrasives, owing to the possibility of deep scratches occurring, but for rough castings No. 70 emery may be used for the preliminary cleaning. After this, a No. 120 emery is employed, with a compressed canvas wheel, followed by No. 160 emery on a felt wheel. The final polish is imparted by buffing on a stitched cotton wheel, using a greasy tripoli compound, followed by treatment on a soft mop with dry lime or rouge.

For sheet metal work preliminary cleaning may be accomplished with the ordinary fine Trent sand and oil on a bob covered with leather and running at a high speed. The second operation is that known as "grease-mopping," and is carried out on a calico mop, using tripoli compound. Finally, the articles are finished upon a soft mop, using dry lime.

For *castings* of a simple pattern, the polishing may be almost entirely accomplished by the *tumbling* process. For rough castings, coarse sand or crushed granite mixed with water to about the consistency of thin mortar may be used as a preliminary. This treatment, although somewhat harsh, is necessary, owing to the peculiar nature of the metal. When the castings have been sufficiently roughed, they are transferred to a wooden or wood-lined metal barrel, and *tumbled* with steel balls or smooth steel punchings in water containing $\frac{1}{4}$ ounce of oxalic acid per gallon. This treatment requires from 2 hours to 2 days, depending upon the size and shape of the castings. The tumbling barrel speed is such that the articles roll round and do not drop across the barrel.

Welding Aluminium and Its Alloys

Aluminium may be welded satisfactorily by the oxy-acetylene and electric welding processes if suitable precautions are taken.

When the oxy-acetylene process is used for sheet metals, strong joints may be obtained if the correct flux and welding rod are used. In the welding of aluminium sheet the edges to be joined are melted together with a welding rod of pure aluminium.

The most important point in welding operations is to remove the invisible film of oxide. This is accomplished by the use of a suitable flux which attacks the oxide almost as soon as it forms. The best

fluxes are those used in a dry condition, the flux being applied by dipping the heated end of the welding rod into the powder and melting up the adherent flux so as to form a kind of skin along the welding rod. Fluxes for aluminium must be kept airtight as they are hygroscopic.

After welding, any excess flux must carefully be washed away with warm water, using a brush.

The welding rod should be of the same composition as the sheet being welded and of the same diameter as the thickness of the sheet, within certain limits. The minimum size of rod used for all sizes of sheet below No. 16 S.W.G. is about No. 14 S.W.G., while, even for very thick sheets, rods of over $\frac{5}{16}$ in. diameter are rarely used.

The electrical welding processes used for aluminium and its alloys include the resistance (spot, seam and butt methods), metallic arc and atomic hydrogen ones. As it is not possible, in the limited space available, to give detailed information on these processes, the reader is referred to the publications on *Electric Welding* and *Aluminium Jointing* issued by The British Aluminium Company, Ltd., King William Street, London, E.C.4, and The Northern Aluminium Company, Ltd., Bush House, Aldwych, London, W.C.2.

Soldering Aluminium and Its Alloys

Aluminium is a difficult metal to solder satisfactorily on account of the thin oxide film always present on its surface; this film must be removed if a good joint is to be obtained. The removal of the oxide film is more important than the composition of the aluminium solder.

Although apparently good joints are obtained with the majority of the proprietary makes of aluminium solder, these joints are liable to a process of progressive weakening due to corrosion of the included flux: many of the joints will not withstand a boiling water immersion test.

Solders used for aluminium are usually electronegative to aluminium, so that in the presence of moisture electrolytic action occurs with a consequent corrosion of the solder at the joint; for this reason it is advisable to protect the joint with paint or varnish.

The three principal methods of soldering which have given satisfactory results are (1) *Hard soldering;* (2) *Soft soldering;* and (3) *Reaction soldering.*

(1) *Hard Soldering.* In this process the solder consists of an alloy of aluminium having a melting point between 500° and 600° C. Many such alloys exist, but the silicon alloy, containing 10–13 per cent of silicon, is undoubtedly the best. The oxide is removed by means of an alkaline halide flux, such as is used for aluminium welding. At the

temperature at which the soldering is carried out the flux is melted and rapidly attacks the oxide, permitting the melted solder to come into contact with clean aluminium and to alloy with its surface. In carrying out the process a gas blowpipe is used as heating medium, but apart from this and the higher temperature required, the process does not differ from the ordinary soldering of brass. The flux is applied on the end of the solder stick, which is melted up and flows readily, sweating the parts together. Certain manufacturers supply silicon alloy solder in the form of a tube with the flux contained inside. Hard soldering with a silicon alloy solder is thoroughly to be recommended as regards ease of application, strength and permanence. Unlike soft soldering, the joint is capable of withstanding the action of boiling water or steam without protection.

(2) *Soft Soldering.* In this process the solder melts at a comparatively low temperature and it is this type of work which has given rise to the widespread view that aluminium is difficult to solder. The reason is that no satisfactory flux is available which will attack the oxide at the low temperature of working, so that the oxide must be removed by mechanical means. After a preliminary cleaning, the metal is heated until the solder melts upon it. The molten solder will not adhere, but it can be made to do so by scraping through it with an old hacksaw blade or other form of scraper to break up the oxide film. Once the film is broken the oxide cannot reform under the solder, and alloying takes place. When the surface is fairly well covered with molten solder the adhesion is improved by rubbing with a wire scratch brush while the solder is still molten, thus breaking up any remaining traces of oxide. After such "tinning," the parts can be sweated together in the ordinary way. Fluxes are sometimes supplied with these solders, but these consist largely of stearin or resin and are of little assistance.

The composition of the solders is not of great importance. They usually consist of zinc and tin with or without small additions of other ingredients.

(3) *Reaction Soldering.* This is a newly developed process which is particularly interesting. The solder is a chemical mixture which is spread on the parts to be jointed and heated by a blowpipe to about 200° C. A chemical reaction takes place which results in the deposition of pure zinc in a molten condition on the aluminium surfaces to be joined. The zinc flows readily between the edges and alloys readily with the aluminium, forming an excellent joint. Such joints are much more permanent than those made by the ordinary soft soldering process.

The Alunize Process

A satisfactory solder known as Alunize,* having a high tensile strength, has been developed for use with aluminium and its alloys, e.g. duralumin and Hiduminium. The cleaned surfaces are heated to a temperature that will just cause the solder to melt and the surfaces are "tinned" with the solder, using a scraper or wire brush to ensure thorough adhesion. After thus coating the joint surfaces more solder is added and the two members are clamped together and allowed to cool.

The solder melts at 160° to 180° C. and has a tensile strength of 20 to 26 tons per sq. in. It has given very good results in aircraft work and for light alloy tubular bicycle frames; also with Elektron alloys.

* Alunize Ltd.

CHAPTER IV

MAGNESIUM AND ITS ALLOYS

IN recent years magnesium has proved of increasing importance in light engineering constructional work on account of the strong light alloys which it forms with small proportions of other elements. Magnesium alloys—of which the Elektron group is an example—are now used for automobile and aircraft parts as forgings, extruded bars, sheets and castings.

Magnesium

This metal in the pure state is of silvery-white appearance and has a specific gravity of 1·74 as compared with 2·705 for pure aluminium. It is obtained commercially from two distinct sources, namely, from sea-water (which contains magnesium salts) and from mineral ores. The Dow Chemical Company of America, which is one of the largest magnesium producing firms in the world, extracts magnesium from the crystalline product known as magnesium chloride hexahydrate. The metallic magnesium is obtained by electrolysis of molten magnesium chloride crystals derived from the hexahydrate salt, which itself is a by-product of the sea-water brines from which the Company extracts salt, bromine and other constituents. Ordinary sea-water contains about 0·1 per cent of magnesium.

The natural ores from which magnesium is obtained by the electro-thermal process include *Brucite* (magnesium hydroxide), *Magnesite* (magnesium carbonate) and *Dolomite* (magnesium associated with calcium as a double carbonate).

The process of extracting magnesium from its ores is a difficult one on account of its high affinity for oxygen. In one modern process the oxygen combined with the magnesium is taken up by coke to form carbon oxides at the high temperature of the electric arc furnace. The mixture of elemental magnesium vapour and carbon oxides thus produced is cooled as quickly as possible to prevent the oxygen from returning to the magnesium. A well-known process, known as the Hansgirg one, employs the method of shock-cooling with large volumes of hydrogen to attain this object. It is necessary to employ a source of low-cost power, such as natural water power, in order to produce magnesium at a reasonable price.

Mechanical and Physical Properties

Although commercially pure magnesium is not employed in engineering, it has other applications in industry, notably as a de-oxidizer, to remove the last traces of oxygen from baths of molten metal or from inside radio valves. It is also used as the principal ingredient of aircraft flares and in photographic flash powder.

Magnesium is not only much lighter than aluminium on an equal volume basis, but it is notably stronger in tension and harder, although at the same time it is much more brittle. In this connection the values given in Table 37 enable a comparison to be made of the mechanical properties of the two pure metals in the rolled and annealed condition.

TABLE 37

MECHANICAL PROPERTIES OF MAGNESIUM AND ALUMINIUM
(Aitchison)

	Magnesium	Aluminium
Density	1·74	2·71
Tensile strength (tons per sq. in.) .	11·0	6·0
Elongation, per cent . . .	5·0	40
Reduction of area, per cent . .	6·0	80
Brinell hardness	33	24
Specific tenacity*	6·32	2·21

* The specific tenacity is the tensile strength divided by the density.

From these results it will be noted that magnesium, with a specific tenacity of 6·32, is nearly three times as strong for its weight as aluminium with a specific tenacity of 2·21.

Magnesium has a relatively low modulus of elasticity, namely, $3·5 \times 10^6$ lb. per sq. in. as compared with 10×10^6 lb. per sq. in. for aluminium; this value is not improved, materially, by alloying it with small proportions of other elements.

As the stiffness of a beam of given depth is proportional to the modulus of elasticity, it follows that a magnesium beam would have only about 60 per cent of the stiffness of a similar one in aluminium; also, for magnesium and aluminium plates of equal thickness, the latter would be about 60 per cent stiffer. This proportion also holds for most aluminium and magnesium alloys.

It is here of interest to note that the ratio of the density to the elastic modulus is very nearly the same for magnesium, aluminium, and iron.

The principal *physical properties* of pure magnesium are as follows—

Specific gravity . . . . 1·74
Weight per cubic inch . . . . . . 0·0627 lb.
Specific heat at 20° C. . . . . . . 0·2456
Thermal conductivity (C.G.S. units) at 18° C. . . 0·376
Coefficient of thermal expansion per °C. . . . 0·0000259
Electrical conductivity (silver = 100) . . . 39·4
Melting point . . . . 651° C.
Atomic weight . . . . 24·32.

Some Other Properties

Magnesium itself is not readily affected by the atmosphere; it is considered to be slightly better than aluminium in this respect. On exposure it becomes covered with a thin bluish grey film of oxide and hydroxide which appears to prevent further attack. As the commercial alloys of magnesium are liable to atmospheric corrosion, methods of producing a protective oxide coating, analogous to the anodic process used for aluminium alloys, are being developed.

The presence of minute impurities in the metal cause accelerated local corrosion. In this connection the commercial metal is of a high standard of purity, a typical sample when analysed showing only 0·08 per cent iron, 0·02 per cent copper, and 0·01 per cent silicon. When magnesium is heated it does not scale at temperatures up to about 450° C., or even up to the ignition temperature.

The mechanical properties of magnesium are affected materially as the temperature is increased; the alloys of this metal are also influenced, but to a different degree, by temperature increase.

The results of some tests made upon a rolled magnesium rod are given in Table 38.*

TABLE 38

STRENGTH OF MAGNESIUM AT ELEVATED TEMPERATURES

Temperature	Ultimate Stress (Tons per sq. in.)	Elongation per cent on 2 in.	Estimated Fatigue Range (Tons per in.) (Haigh)	Impact 5 × 5 mm. Charpy Ft.-lb.
Heated 5 hours at 150° C. . .	6·0	37	± 1·5	1·09
Heated 5 hours at 250° C. . .	2·7	98	—	1·48
Heated 5 hours at 350° C. . .	1·13	104	—	—

* "Mechanical Properties of Pure Magnesium and Certain Magnesium Alloys," Archbutt and Jenkin; Aeron. Res. Com., *R. and M.*, No. 1,287 (February, 1929).

Magnesium is readily attacked by weak acids, and also by saline solutions; it is not affected, however, by most alkaline solutions.

Magnesium ignites fairly easily at or above its ignition temperature; its use in the form of magnesium ribbon and in flashlight powders for photographic purposes is well known in this respect. In view of its tendency to ignition certain precautions have to be taken when machining magnesium, as a considerable amount of heat may be developed, more particularly when high machining speeds are employed in conjunction with blunt tools, so that the turnings, chips or powder burn. Turnings when dry will not ignite spontaneously, but they should not be allowed to stand in the open. They are best stored in a covered wooden box and can be used as scrap after pressing into briquettes.

On account of its relatively high specific tenacity and good heat conductivity magnesium, before its alloys became developed, was used for the pistons of experimental petrol engines. The pistons were machined from the solid and proved expensive; moreover, the rapid decrease in mechanical strength with temperature—for the working temperatures at the crown of the piston were from 350° C. to 380° C. —necessitated greater thicknesses of the metal, so that much of the original benefit of lightness was lost thereby.

Magnesium Alloys—General Considerations

Magnesium by itself is not sufficiently strong to be used as a light engineering metal as an alternative to the available aluminium alloys. It differs from most of the commoner metals, e.g. iron, aluminium, copper and nickel, in having crystals of the hexagon instead of the cubic system, a circumstance which has an important bearing upon the mechanical and metallographic behaviour of this metal—as well as upon its alloying properties.

It has been established* that solid solutions which are necessary for strengthening alloys cannot be formed to any appreciable extent if the atomic diameter of the metal addition differs from that of the solvent metal by more than about 14 per cent. When this rule is applied to magnesium, some of the more useful metals that come within the percentage limit mentioned include aluminium, silver, cadmium, tin, antimony, lead and bismuth. Experimental investigations on the alloys of magnesium indicate that, with the exception of *aluminium* and *cadmium*, the other metals mentioned produce alloys which are brittle and reactive. There are, however, certain other

* Hume Rothery.

metals outside the group in question which, in small percentages only, can form solid solutions. These include manganese, calcium, cerium, zinc, nickel and cobalt.

The commercial binary and ternary magnesium alloys contain either two or three of these metals with small additions of others from the two series previously mentioned. In this connection, the following systems* have been investigated to a certain extent with varying degrees of success—

Magnesium-Manganese (Mn up to 2·5 per cent).

Magnesium-Aluminium (Al from 8 to 12 per cent).

Magnesium-Cerium (Ce 10 per cent, with or without additions of Co and Mn).

Magnesium-Aluminium-Silver (Al, 7·5 to 8·5; Ag, 2·5 to 3·0 per cent, with additions of Zn, Mn, and Ca).

Magnesium-Aluminium-Zinc (Al, up to 11 per cent; Zn, up to 3·5 per cent).

Magnesium-Aluminium-Cadmium (Al, 8 per cent; Cd, 8 per cent).

Magnesium-Cadmium (Cd up to 20 per cent).

Magnesium-Cadmium-Zinc (Cd, 4 per cent; Zn, 4 per cent).

In general, magnesium alloys, on account of their hexagonal crystal structure, are difficult to work, as they exhibit marked directional properties. This structure, however, easily twins and in this connection special manufacturing processes have been evolved for breaking down the structure by repeatedly changing the direction of stress; in this manner the ductility has been improved appreciably.

Effects of Metals on Mechanical Properties of Magnesium

In view of the conclusions outlined in the preceding section it is of interest to consider the effects of certain metals, namely, zinc, cadmium, and aluminium, upon the mechanical properties of magnesium.

Fig. 46 illustrates the mechanical properties of these binary alloys for the different percentages of added metals shown by the abscissae of the curves. The alloys in each case were in the form of extruded bars from which the test specimens were machined, and the graphs are based upon experimental values by L. Aitcheson.†

In connection with the results given for aluminium alloys it may be mentioned that the reduction of area diminished progressively from

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* "Materials of Aircraft Construction," H. J. Gough, *Journ. Roy. Aeron. Soc.* 26th May, 1938.

† "Light Alloys for Aeronautical Purposes with Special Reference to Magnesium," L. Aitchison. *Journ. Roy. Aeron. Soc.*, 14th December, 1933.

29 per cent for 2·5 per cent aluminium down to 4·4 per cent for the
13·14 per cent aluminium alloy.

Whilst the tensile strength values for the alloys with more than
about 5 per cent aluminium were a marked improvement upon that
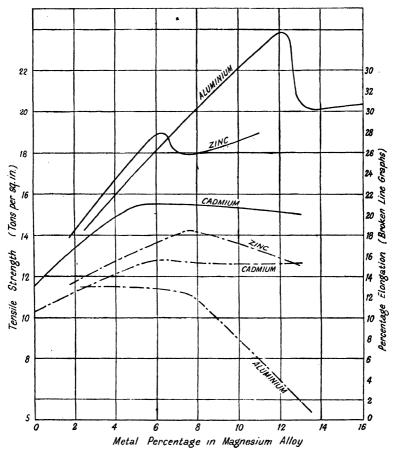
FIG. 46. EFFECT OF OTHER ELEMENTS ON THE MECHANICAL PROPERTIES
OF MAGNESIUM

for the pure metal, namely, 11 tons per sq. in., the ductility—as shown
by the elongation and reduction of area values—is not satisfactory
from the engineering application point of view. In order to improve
this ductility the effect of small additions of other metals was investi-
gated. *The addition of zinc* in percentages up to about 5 to magnesium

alloy containing up to 10 per cent aluminium was found to improve the ductility to an appreciable extent, as shown by the results given in Table 39.

TABLE 39

MAGNESIUM-ALUMINIUM-ZINC ALLOYS (EXTRUDED)

Aluminium per cent	Zinc per cent	Maximum Stress Tons per sq. in.	Elongation per cent	Reduction of Area per cent
1·22	1·26	13·8	17·3	47·0
3·96	1·29	15·8	17·6	36·15
3·75	3·10	18·1	20·0	34·65
2·34	4·06	17·6	21·3	39·9
5·53	3·90	22·5	16·25	17·0
9·97	2·33	22·7	11·5	13·5
6·14	4·12	22·0	12·7	18·5
4·97	3·08	19·8	16·5	24·60
5·22	5·08	21·0	17·2	25·2

The addition of cadmium to magnesium-aluminium alloys was also shown to give a marked improvement in tensile strength values, and to benefit the ductility, but not to the same extent as the zinc. Some experimental values given by L. Aitchison are shown in Table 40.

TABLE 40

MAGNESIUM-ALUMINIUM-CADMIUM ALLOYS (EXTRUDED)

Aluminium per cent	Cadmium per cent	Maximum Stress Tons per sq. in.	Elongation per cent	Reduction of Area per cent
9·47	1·25	22·1	8·7	9·76
10·28	1·96	22·0	12·6	17·3
9·70	2·08	22·4	10·56	14·7
9·50	3·76	22·05	11·2	16·25
12·44	1·13	22·9	7·2	6·0
12·99	2·10	23·0	4·2	5·9

The effect of manganese in magnesium alloys is of interest since it has been shown that this metal, in small percentages, improves the corrosion resistance.

The general results of an investigation into the effect of additions of manganese indicated that, between the limits of 0·18 and 2·6 per cent of manganese, the tensile strength values were between 13·7 and 13·0 tons per sq. in. and percentage elongations from 6·0 down to 3·5.

The effect of silicon in percentages up to 2·19 gave tensile strengths of 11·6 to 17·1 tons per sq. in.; elongations between 18·8 and 4·2 per cent, and reductions of area of 31·3 to 5·9 per cent. A typical alloy containing 0·56 per cent of silicon gave a tensile strength of 14·2 tons per sq. in. with 7·3 per cent elongation and 13·4 per cent reduction of area. Greater ductility was only obtained at the expense of a loss of tensile strength.

Magnesium-copper Alloys

A series of alloys of magnesium and copper of particular interest on account of their good thermal and electrical conductivities has been investigated by W. R. D. Jones and W. T. Cook.*

The magnesium-copper alloys up to 13 per cent copper are the more important in this respect and for approximate purposes may be regarded as having about twice as good thermal and electrical conductivities as the magnesium-aluminium series mentioned. In the wrought state 13 per cent alloy has a tensile strength of 15·0 tons per sq. in. with 6 per cent elongation on 2 in. In the commercial forms of magnesium alloys three types have been exploited, viz., the binary alloys with copper and aluminium respectively and the alloys containing zinc as the principal addition, with minor additions of other metals, including copper. All three types are easily cast, and can be hot-worked by forging, rolling, etc. As a general rule these alloys are about 30 per cent lighter than aluminium-silicon alloy containing 13 per cent silicon, which is one of the lightest of the other commercial aluminium alloys.

Copper is almost completely insoluble in magnesium; it forms an insoluble compound Mg_2Cu. In magnesium containing 0·06 per cent copper the presence of the compound is readily seen under the microscope. On increasing the amount of copper the tensile strength is increased up to about 2·5 per cent copper, beyond which the strength decreases. The ductility is at once decreased on the addition of copper and becomes almost negligible beyond 6 per cent.

Magnesium Casting Alloys

A special feature of the commercial casting alloys of magnesium is that these can be made in large and complicated shapes as sand-castings with no more difficulty than similar ones in aluminium alloy. It is also possible to make gravity and also pressure castings on a commercial scale and such castings are now in general production.

Magnesium alloys are employed for castings that are not too heavily

* "Magnesium and Its Alloys," W. R. D. Jones and W. T. Cook, *Journ. Roy. Aeron. Soc.* (Oct., 1926).

stressed and the ductility of these can be improved by an annealing treatment which results in more of the alloying elements entering into solid solution. The hardness can be increased, but at the expense of the ductility, by a subsequent heat-treatment which results in the fine precipitation of a constituent.

Among the advantages of modern magnesium-alloy castings are the reduction of weight (about 40 per cent of aluminium alloys); freedom from brittleness; absence of pinholes and inclusions and greater stiffness for a given weight, or the same stiffness for a lower weight. There is a fairly wide range of compositions for casting alloys but the general composition of these is defined by the following limits—

Aluminium	.	.	.	.	0·2 to 11·0 per cent
Zinc	.	.	.	.	0·2 to 3·5 ,,
Manganese	.	.	.	.	0·5 to 2·5 ,,

The mechanical properties of these alloys vary appreciably but there are two essentially different types within the group, typical compositions of which are as follows—*

(1) Al, 8·5 per cent; Zn, 3·5 per cent; Mn, 0·5 per cent (maximum values).

(2) Al, 0·2 per cent; Zn, 0·2 per cent; Mn, 2·5 per cent (maximum values).

The mechanical properties of these alloys are as follows—

	0·1 per cent Proof Stress Tons per sq. in.	Tensile Strength Tons per sq. in.	Elongation per cent
(1) Sand cast . .	4·5–5·5	9–11	3– 5
Sand cast and solution heat-treated .	4·5–5·5	14–16	9–14
(2) Sand cast . .	1·5	6–7	3– 5

The first type has characteristic properties of its class of casting alloys whilst the second is used for lightly stressed parts; this alloy can be welded quite easily.

A series of casting alloys favoured in Germany is that containing aluminium and zinc with a small addition of manganese. If the percentages of aluminium and zinc are indicated by suffix numbers then the aluminium series can be written as follows—

$$\left.\begin{array}{l} Mg - Al_{10} - Zn_5 \\ Mg - Al_6 - Zn_3 \\ Mg - Al_4 - Zn_3 \\ Mg - Al_3 - Zn_1 \end{array}\right\} + 0·5 \text{ per cent Mn.}$$

* *Ante*, page 105, note (upper reference).

The 10 per cent aluminium alloy is heat-treated by annealing alone or together with temper hardening. This treatment raises the tensile strength of the casting from an original value of 11·2 tons per sq. in. to a maximum of 17·9 tons per sq. in., with a corresponding increase in hardness.
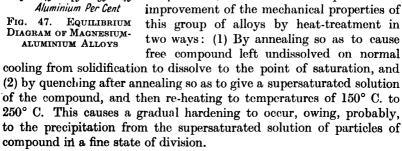
Another alloy of magnesium and silicon is employed for liquid-tight castings.

Heat-treatment of Cast Alloys
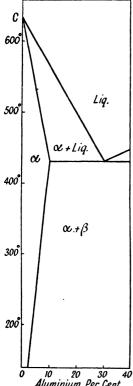
The alloys of magnesium containing aluminium, zinc and manganese mentioned previously attain their full mechanical strength properties after suitable heat-treatment.

The magnesium-aluminium alloys also develop their full mechanical properties after suitable heat-treatment.

The approximate equilibrium diagram of this series is shown in Fig. 47, from which it will be seen that at normal temperature magnesium is capable of retaining up to about 2·3 per cent of aluminium in solution; the slowly cooled or annealed alloy therefore exhibits a homogeneous structure. Beyond about 9 per cent of aluminium a second constituent — probably the intermetallic compound Al_2Mg_3—appears. The solubility of the Al_2Mg_3 compound in the solid magnesium increases appreciably with rise of temperature; this fact makes possible the improvement of the mechanical properties of this group of alloys by heat-treatment in two ways: (1) By annealing so as to cause free compound left undissolved on normal cooling from solidification to dissolve to the point of saturation, and (2) by quenching after annealing so as to give a supersaturated solution of the compound, and then re-heating to temperatures of 150° C. to 250° C. This causes a gradual hardening to occur, owing, probably, to the precipitation from the supersaturated solution of particles of compound in a fine state of division.

In regard to the aluminium-zinc-manganese series of cast alloys two methods of heat-treatment, namely, solution heat-treatment and

FIG. 47. EQUILIBRIUM DIAGRAM OF MAGNESIUM-ALUMINIUM ALLOYS

precipitation hardening-treatment, similar to those previously mentioned, are employed. The former method consists in heating the alloy at 420° C. for 24 hours, during which period the alloy is protected by sulphur dioxide or by using a dichromate salt bath.

The precipitation method consists in heating the alloy at a given temperature between 150° C. and 200° C. for a period of 12 hours, or longer.

Commercial Magnesium Alloys

The commercial alloys include the Elektron series, Magnuminium and other alloys made to the D.T.D. Specifications. In America the Dow Metals, made by the Dow Chemical Co., cover a wide range of applications in the form of sand and die-castings, forgings, plate, bar, extrusions, etc. Similar alloys to about nine different specifications of the American Society of Testing Materials are made by the American Magnesium Corporation and Bohn Aluminium and Brass Corporation. These alloys are mostly of the aluminium, zinc and manganese group.

The Elektron series, originally developed in Germany by the Chemische Fabrik Griesheim Elektron and subsequently by the I.G. Farbenindustrie A.G., was introduced into this country in 1922 by Messrs. F. A. Hughes, Ltd., and has since been taken up under licence by a number of casting-producing, sheet, forging and extrusion concerns. By 1934 the demand for Elektron alloys had grown to such an extent that a new company, now known as Magnesium Elektron, Ltd., was formed for the production in England of raw magnesium and its alloys.

The Elektron group covers a wide range of light magnesium alloys including sand, gravity and pressure die-casting ones and wrought alloys in the form of forgings, pressings, extruded rods, bars, angles, sections, tubes, rolled sheet, etc.

These alloys conform to D.T.D. Specifications for chemical compositions and the sand cast alloys.

The compositions, equivalent D.T.D. Specifications and mechanical properties of the cast and wrought Elektron alloys are given in Table 41.

Die-casting Alloys

In regard to the die-casting Elektron alloys, such as AZ.91, these give very satisfactory results and are used in a number of instances to replace die-cast aluminium parts. The usual die-casting practice is followed, but in addition special precautions should be taken. Thus, instead of employing hand ladles dipped into the molten metal

TABLE 41

"ELEKTRON" ALLOYS IN GENERAL USE, WITH D.T.D. SPECIFICATIONS

Alloy (A.M. Specification)	Elektron Alloy	Form	Al %	Zn %	Mn %	Mg %	Cu %	Si %	Impurities %	Proof Stress 0.1% t.s.i.†	Maximum Stress t.s.i.†	Elongation on 2 in. %	Brinell Hardness 500/10/30
D.T.D. 136A	AZ.91	As sand cast	9–11	3.5 max.	0.5 max.	Rem.			1.5 max, including Cu, Pb, Fe, Si	4.5–5.5	8–10	1–3	55–65
D.T.D. 281	AZ.91	Heat-treated (solution treatment only)	9–11	1.0 max.	0.5 max.	Rem.			1.0 max, including Cu, Pb, Fe, Si	5–6	14–16	7–9	55–65
D.T.D. 285	AZ.91	Heat-treated (solution and precipitation treatments)	9–11	1.0 max.	0.5 max.	Rem.			1.0 max, including Cu, Pb, Fe, Si	7–9	15–17	1–3	75–85
D.T.D. 59A	A.8	As sand cast	8.5 max.	3.5 max.	0.5 max.	Rem.	0.4 max.	0.4 max.	Pb 0.4, Sn 0.4, Fe 0.1 max.	4.5–5.5	9–11	3–5	50–60
D.T.D. 289	A.8	Heat-treated (solution treatment only)	8.5 max.	3.5 max.	0.5 max.	Rem.			1.0 max, including Cu, Pb, Fe, Si	4.5–5.5	14–16	9–14	50–60
D.T.D. 59A	AZG	As sand cast	8.5 max.	3.5 max.	0.5 max.	Rem.	0.4 max.	0.4 max.	Pb 0.4, Sn 0.4, Fe 0.1 max	4.5–5.5	9–11	3–5	50–60
D.T.D. 289	AZG	Heat-treated (solution treatment only)	8.5 max.	3.5 max.	0.5 max.	Rem.			1.0 max including Cu, Pb, Fe, Si	4.5–5.5	14–16	8–10	45–55
D.T.D. 140A	AM.503	As sand cast	0.2 max.	0.2 max.	2.5 max.	Rem.	0.2 max.	0.4 max.	0.5 max.	1.5	6–7	3–5	35–45
D.T.D. 259	AZM	As extruded	11.0 max.	1.5 max.	1.0 max.	Rem.			1.5 max.	9–12	18–22	*Elongation on* $4\sqrt{a}$ 12–16	55–60
D.T.D. 88B	AZM	As forged	11.0 max.	1.5 max.	1.0 max.	Rem.			1.5 max.	8–10	18–20	10–12	65–70
D.T.D. 142	AM.503	Extruded	0.2 max.	0.2 max.	2.5 max.	Rem.	0.2 max.	0.4 max.	0.5 max.	8–9	15–17	3–10	40–50
D.T.D. 118	AM.503	Rolled	0.2 max.	0.2 max.	2.5 max.	Rem.	0.2 max.	0.4 max.	0.5 max.	6–8	12–15	3–10	39–42
Draft D.T.D. 322	AZ.855	As forged	7.5–8.5*	0.4–5	0.15–0.25	Rem.				11–14	18–22	8–15	65–75

* Actual "Elektron" composition. † Tons per sq. in.

—when oxide and slag inclusions might result—a tilting furnace is used for pouring purposes. The metal is superheated in the usual way. It is essential that the entry of the molten metal into the die should be as tranquil as possible, the die being tilted for this purpose.

FIG. 48. UNMACHINED CRANKCASE IN ELEKTRON FOR GARDNER 6LW HIGH-SPEED DIESEL ENGINE

The dies are kept at a high temperature by external heating and are well vented to allow the air to escape quickly. They are washed with a mixture of boric acid and French chalk in water.

The Elektron AZ.91 alloy is used for ordinary die-castings and has somewhat better die-casting properties than the A.8 alloy, but not

FIG. 49. SOME TYPICAL ELEKTRON FORGINGS

quite as good mechanical properties; the latter alloy is used also for pressure die-castings and parts have been produced with minimum wall thicknesses of 0·04 in.; normally, however, 0·05 in. appears to be the lower limit.

The AZ.91 alloy as sand cast has a tensile strength of 8 to 10 tons per sq. in., with 1 to 3 per cent elongation, but when solution and

precipitation heat-treated gives 15 to 17 tons per sq. in. with the same elongation; when solution-treated only, the tensile strength is slightly less, namely, 14 to 16 tons per sq. in., but the ductility is improved as shown by the 7 to 9 per cent elongation value.

The sand cast A.8 alloy has a tensile strength of 9 to 11 tons per sq. in. with 5 to 3 per cent elongation. When solution heat-treated the respective values are 14 to 16 tons per sq. in. and 14 to 9 per cent.

Applications of Elektron Alloys

The cast and wrought alloys have applications covering a fairly wide range in automobile, aircraft and industrial constructions where
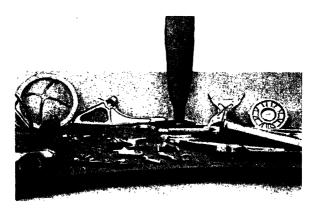
FIG. 50. SOME MISCELLANEOUS ELEKTRON FORGINGS

lightness combined with high strength are primary considerations. As the metals have excellent machining properties manufacturing costs on this account can be kept low.

In aircraft applications, Elektron alloys are employed for crankcases of engines, covers, brackets, and similar lightly stressed components; and in the construction of fuselages and fairings, steering parts, seats, petrol and oil tanks, landing wheels and retractable landing gear fittings, instrument boards, brake components, blades for variable-pitch airscrews, etc. In this connection development work is still proceeding with the object of improving still further the mechanical properties of these alloys.

In the motor transport industry, where the present mode of taxation has led to the demand for the maximum power/weight ratio in order to give good performance, and as big a pay load as possible, these alloys are now being employed for engine crankcases, gear-boxes,

back axles, brackets and fittings, thereby enabling marked reductions of weight to be effected over steel, cast iron and aluminium parts.

Among the numerous industrial applications of Elektron are those of parts of portable apparatus such as rammers, compressors, pumping sets ; also wireless and welding sets, machine tools, cameras, binoculars and scientific instruments where reduction in weight has important practical advantages. The output obtained from machines used in making cigarettes and containers, also textile and knitting fabrics, is increased by the substitution of Elektron for rapidly reciprocating parts. It has not been possible in the space available to deal very fully with this subject, but for more detailed information the reader is referred to the references below.*

Wrought Magnesium Alloys

Magnesium alloys with small proportions of added metals can be extruded, rolled and forged, but with more difficulty and to a more limited extent than in the case of aluminium alloys.

The principal reason for this is on account of the previously mentioned hexagonal crystal structure of these alloys which renders it much more difficult to deform the metal than with the cubic system of copper or aluminium. In the latter system there is a number of similar planes on which slip can occur, so that considerable deformation is possible by alternate slipping in several planes. With the hexagonal system slip can only take place at lower temperatures on a single set of planes, i.e. in one direction, so that deformation is limited.

As commercial alloys consist of crystals arranged with their basal planes in various directions, the process of distortion or mechanical working of the metal is strictly limited. This limitation is reached much sooner in the alloys of magnesium than in the pure metal. It is not possible in the space available to discuss the subject of crystal deformation more fully, but the reader will find an authoritative account in a paper by C. H. Desch, F.R.S.,† and in a book by J. L. Haughton and W. E. Prytherch.‡

  * *Elektron Magnesium Alloys*, F. A. Hughes Ltd.
"Magnesium and Its Alloys," F. A. Fox, *Metal Industry*, 14th, 21st and 28th June, and 5th July, 1940.
Elektron. Some Principles of Casting Design, H. Reininger, Leipzig (F. A. Hughes Ltd.).
"New Uses of Elektron Sheet," D. B. Winter, *Aircraft Production*, May, 1941,
"Elektron Tanks," *Flight*, 8th February, 1940.
  † "Magnesium Alloys," C. H. Desch, *Journ. Roy. Aeron. Soc.*, 14th January, 1937.
  ‡ *Magnesium and Its Alloys*, J. L. Haughton and W. E. Prytherch; Dept. Scient. and Industr. Research. H.M. Stationery Office, Kingsway, London, W.C.2 (1937).

The following are the principal conclusions arrived at—

(1) Mechanical working or deformation of magnesium alloys must be carried out at temperatures ·well above atmospheric, namely, between 225° and 300° C.

(2) The crystal grains should be as fine as possible, usually by casting from a high temperature.

(3) The direction of working the metal should be changed frequently. Thus, if the metal can be squeezed, first in one direction and
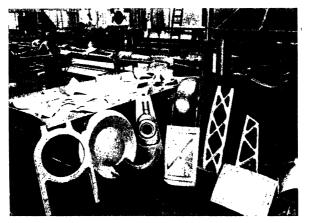
FIG. 51. MISCELLANEOUS ELEKTRON SHEET METAL PRESSINGS

then in another, a much greater degree of deformation is possible than in a single operation.

(4) If the ingot is broken down by rolling or hammering cracking readily occurs, even for small stage reductions. When, however, the surfaces of the mass of metal are confined much greater deformation without cracking is possible.

(5) Two satisfactory methods of working are extrusion and pressing between heated dies; these methods are used commercially.

(6) The speed of working, i.e. extrusion or pressing, should be kept as low as possible, certainly much lower than for aluminium alloys.

(7) When a series of operations is necessary, as when pressing, each successive pressing should be at a lower temperature than the previous one.

(8) Rolling to form sheets gives a structure with highly directional properties. The operation should be carried out at a slow speed, as mentioned in (6), and with the metal heated; the direction of rolling

should be altered frequently. The last operation should be a reduction of 10 per cent with the metal cold, followed by annealing.

(9) When pressing to any large extent intermediate annealings are generally necessary, but there is always a danger of excessive grain growth.

(10) By repeatedly changing the direction of stress, or rolling, the crystal structure can be broken down largely as a result of repeated crystal twinning and as the directional properties are lessened so the ductility is improved. The use of staggered rolls is recommended for this purpose.

Some Wrought Alloys

The addition of cadmium to magnesium, as shown in Fig. 46, does not alter the tensile strength appreciably, but the alloys are very ductile and can be improved by mechanical working. Rolled strip containing cadmium 4 per cent and zinc 4 per cent has a tensile strength of 17·2 tons per sq. in., with 22 per cent elongation. This alloy can be spun into simple forms, but intermediate annealings are necessary.

The magnesium-manganese group provides *an alloy which is notable for its weldability* and *corrosion resistance*. The alloy in question has a maximum percentage of manganese of 2·5 with aluminium up to 0·2 per cent and zinc up to 0·2 per cent.

This alloy, which is much used in sheet form for aircraft fuel and oil tanks, containers and panels, etc., has a tensile strength of 12 to 15 tons per sq. in., with a 0·1 per cent proof stress of 6 to 8 tons per sq. in., and an elongation of 10 to 7 per cent.

Three widely used alloys in the magnesium-aluminium group which are employed in aircraft construction are represented by the examples given in Table 42.

In the case of highly stressed components the proof stress and tensile strength should be increased as much as possible by mechanical working and, where possible, by age-hardening.

*A high-strength magnesium alloy** containing silver—which has been shown to have a beneficial effect upon the strength properties of certain magnesium alloys—contained 8 per cent of aluminium, 8 per cent of cadmium and 2 per cent of silver. When made in the form of forged bars of 1 in. diameter and after a treatment consisting of heating for 2 hours at 140° C., quenching and ageing for 6 days at 130° C., it gave a tensile strength of 27·6 tons per sq. in.; 0·1 per cent proof stress of 19·5 tons per sq. in., and elongation of 4·2 per cent.

* *Ante,* page 105, note (upper reference).
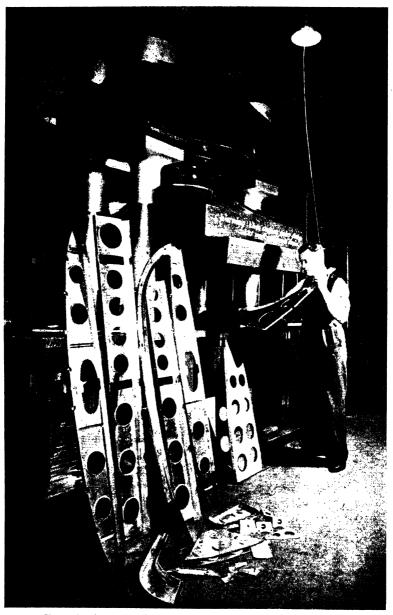
FIG. 52. AIRCRAFT SHEET METAL PARTS MADE ON 1000-TON
RUBBER-FACED HYDRAULIC PRESS

(de Havilland Aircraft Co.)

TABLE 42

WROUGHT MAGNESIUM-ALUMINIUM ALLOYS (Gough)

Application	Composition			Mechanical Properties		
	Al (max.)	Zn (max.)	Mn (max.)	0·1 per cent Proof Stress (Tons per sq. in.)	Tensile Strength (Tons per sq. in.)	Elonga-tion per cent
Sheets . . .	9	1·5	1·0	7	16	10
Bars and extrusions .	11	1·5	1·0	9–11	14–17	5–10
Crankcase ' and air-screw forgings .	11	2·0	1·0	10–12	17	5

Other silver-containing alloys investigated by C. H. Desch gave the results shown in Table 43.

TABLE 43

HIGH-STRENGTH WROUGHT MAGNESIUM (SILVER CONTENT) ALLOYS

Composition (per cent)					Mechanical Properties		
Al	Ag	Zn	Mn	Ca	Tensile Strength (Tons per sq. in.)	0·1 per cent Proof Stress (Tons per sq. in.)	Elonga-tion per cent
8·0	2·5	—	0·4	0·2	25·2	17·0	3·5
7·5	2·7	0·7	0·4	0·3	25·8	17·3	6·0
8·5	3·0	—	0·3	0·2	25·1	16·4	4·0

The specific tenacities of the four alloys mentioned are approximately 13·9 to 15·2, values which are of special interest in comparison with those of the strong light aluminium alloys (wrought) such as Y-alloy, R.R.56, Super-duralumin and duralumin, namely, 8·6, 9·5, 10·7 and 8·9 respectively.

In the case of airscrew blades made from relatively large forgings in similar alloys to those given in Table 42, the metal without age-hardening gave a tensile strength of 20 to 23 tons per sq. in.; 0·1 per cent proof stress of 12 to 14 tons per sq. in.; elongation of 11 to 5 per cent and Wöhler fatigue range of ± 7·5 to ± 8·5 tons per sq. in.

Fatigue Strength of Magnesium Alloys

Although the fatigue strength of the best high-strength magnesium alloys is less than that of the corresponding aluminium alloys, in view of the fact that the former alloys are only about 60 per cent of the weight of the latter the actual values of this strength are of importance from the point of view of light engineering structures.

In this connection the following comparison values of fatigue limits are of special interest. The Wöhler values given are for 20 million reversals of stress—

TABLE 44

FATIGUE LIMITS OF WROUGHT ALUMINIUM AND MAGNESIUM ALLOYS (Tons per sq. in.)

Pure Magnesium	Electron AZM	Duralumin B	Duralumin F	R.R.56
± 4·46	± 8·9	± 9·5	± 11·5	± 10·7

Strength at Elevated Temperatures

As in the case of pure magnesium, the light alloys of this metal usually show a marked falling off in tensile strength as the temperature is increased. Investigations made at the National Physical Laboratory* on the influence of various metal additions upon the strength of magnesium alloys at elevated temperatures indicated that the metals which strengthen magnesium include aluminium, silver, manganese, calcium, nickel and cerium; combinations of two metals were found to have a greater effect than for one alone. Calcium, even in proportions as low as 0·35 per cent, has also the useful properties of producing a lighter alloy than magnesium and improving the casting properties. Cerium in the proportion of 1 per cent has a marked strengthening effect at 300° C.; when nickel is also added, the hardness is similar to that of Y-alloy, but the alloy reduces the corrosion resistance.

In connection with the strength of magnesium alloys at elevated temperatures some comparative values by L. Aitchison are reproduced in Table 7, on page 16. Mention is also made of a special alloy having a tensile strength of 7·4 tons per sq. in. at 300° C.

Petrol Engine Alloys

In regard to the use of magnesium alloys in petrol engines, for parts such as crankcases, their behaviour in creep, i.e. when subjected

* *Ante*, page 115 ,note (lower reference).

to prolonged stress at a given temperature, is important; the available information on this subject is rather limited at present. Other factors which are concerned with *the use of magnesium alloys for pistons* include their permanence of dimensions when alternately heated to working temperatures and cooled, resistance to fatigue, corrosion resistance and thermal conductivity. It may be added, as evidence that the difficulties previously associated with the use of these alloys for pistons are being overcome, that such experimental pistons have been tried out in engines under overload conditions and over appreciable periods of operation with satisfactory results.

Thermal Properties

The coefficient of linear expansion of magnesium alloys between 20° and 200° C. is about $27 \cdot 0 \times 10^{-6}$ for cast alloys and $26 \cdot 8 \times 10^{-6}$ for the wrought ones. The corresponding values between 20° C. and 300° C. are $28 \cdot 0 \times 10^{-6}$ and $27 \cdot 8 \times 10^{-6}$ respectively. It should be mentioned that the value of the coefficient varies a little with the composition and condition of the metal.

The *thermal conductivity* of magnesium alloys is $0 \cdot 32$ C.G.S. units at 18° C.; this value does not vary appreciably for the commercial alloys.

Corrosion of Magnesium Alloys

The subject of the corrosion of these alloys has received a good deal of attention in recent times and the investigations of Bengough, Whitby, Desch, Schmidt and others, have established certain facts which may be summarized, briefly, as follows—

(1) Under normal inland atmospheric conditions magnesium alloys, even after prolonged exposure, become coated only with a white or greyish-white film, whereas steel or iron under similar conditions would be thickly coated with rust.

(2) Cast alloys have a much greater resistance to corrosion, on account of the actual cast skin, than wrought alloys.

(3) No addition of any at present known alloying metal in the usual small quantities necessary for the light magnesium alloys will inhibit corrosion although, as previously mentioned, manganese has an appreciable influence in regard to corrosion resistance.

(4) Chlorides cause accelerated corrosion of magnesium alloys and tend to break down any protective film on the surface. Thus, sea atmospheres, which contain suspended salt particles, are particularly harmful, whilst sea-water has a more marked corrosive action. In this

connection it is stated that, in Berlin, Elektron bus wheels have been in use for some years, but the only serious corrosion that had occurred was due to the salt used for melting snow in the streets.

(5) Excessive corrosion of castings occurs if particles of flux or slag containing chlorides are embedded in the metal. These set up centres of intense local corrosion leading to complete destruction. Modern casting methods, however, obviate the possibility of entrapped flux.

(6) Airscrew blades of magnesium alloy, apart from liability to corrosive action by air containing salt particles, are liable to abrasion of the leading edges by dust particles and raindrops due to the high striking velocity. This effect occurs even when the surfaces are protected by chromate treatment, varnishes, etc.

(7) Fuels containing lead tetraethyl are liable, under certain conditions, to attack sheet magnesium alloy tanks. Whilst neither lead tetraethyl nor its ethylene dibromide content alone attacks the metal, when both are present, together with water, reactions can occur resulting in the deposition of lead which has a marked electrolytic action on the metal. Certain organic substances, such as quinoline (1 per cent), in the fuel will prevent this action. A method sometimes used for fuel tanks is to insert a cartridge containing potassium fluoride, which will absorb the water; then the dry components of the leaded fuel are without action. More recently this method has been superseded by the calcium-chromate cartridge one.

(8) Lead compounds must be avoided in protective paints on account of the intense local electrolytic action previously mentioned.

(9) Intercrystalline corrosion is not experienced with magnesium alloys of the type considered in this section.

Protective Measures

Magnesium alloy fittings that have to be stored or protected for limited periods may be coated with lanolin or treated superficially with cellulose or synthetic resin varnishes, zinc chromate or zinc oxide base paints. Exposed parts of structures should be protected by one of the modern chemical protective coating methods, e.g., chromate, fluoride or selenium. The anodic process used for aluminium alloys cannot be applied to magnesium ones.

The chemical coating methods adopted give a surface layer of protective material which is non-porous and adhesive and acts as a base for the application of paint or varnish.

The usual *chromate protection process* consists in first degreasing the parts in a petrol or caustic soda bath, followed by immersion in a

solution of 15 parts of potassium dichromate with 20 to 25 parts of concentrated nitric acid (1·25 S.G.) in 100 parts of cold water. The immersion period is 1 to 2 minutes for coating and ½ min. for sheet. The parts are then washed thoroughly in cold water and placed in a finishing bath of ½ per cent of potassium dichromate maintained at 65° to 75° C. The treatment in question gives a golden colour.

Another process, developed by the R.A.E., which has been used on Elektron alloys to give a field grey to black finish consists in first placing the parts in a pickling bath of 10 per cent nitric acid in water. Afterwards they are quickly transferred to a bath maintained at 95° to 100° C., consisting of 1·5 per cent potassium dichromate, 1 per cent alum and 0·5 per cent caustic soda in water. With short immersions of 1 hour the grey finish is obtained, but by prolonging this period to about 10 hours an ebony black surface results. An advantage of this method is that it can be applied to precision finished parts without causing any dimensional changes.

The selenium process due to G. D. Bengough and L. Whitby consists, briefly, in dipping the alloy parts at atmospheric temperatures in a solution of 10 per cent selenious acid in water to which has been added 0·1 to 0·5 per cent of sodium chloride; this gives a coating of metallic selenium. Whilst this coating is satisfactory under atmospheric conditions and against certain reagents it is not recommended for salt air or salt water conditions, but forms a useful base for protective paints or varnishes.

The results of sea-water spray tests on Elektron AZM alloy showed that when the original alloy was selenium-coated it had a tensile strength of 18·4 tons per sq. in. with 14 per cent elongation.

When painted and stored for 4 months the tensile strength and elongation values were practically unchanged, but after a further 4 months' exposure to sea-water spray the tensile strength fell to 16·7 tons per sq. in., and the elongation to 6 per cent—due to corrosion effects.

Similarly, when the alloy was treated by the R.A.E. chromate method the original tensile strength was 18·9 tons per sq. in. with 15·5 per cent elongation. After painting and storing for 4 months, the respective values were 19·1 tons per sq. in. and 13·5 per cent, whilst after a further 4 months' exposure to salt water spray the respective values were 12·8 tons per sq. in. and 2·5 per cent.

Applications of Magnesium Alloys

On account of their high specific tenacity values modern alloys of magnesium have a fairly wide range of applications in automobile

and aircraft engineering, as well as in general light engineering and industrial constructions.

In the *automobile field*, the cast alloys are employed for crankcase and gear-box castings, in place of aluminium alloys, for brake drums and brake shoes, commercial vehicle wheels and engine covers, e.g. valve-rocker gear, timing gears, oil sumps, etc. Other examples of the use of these alloys include motor cycle crankcases and rear axle worm gear castings for commercial vehicles.

Crankcase castings, made by the sand-casting process, enable an appreciable amount of weight to be saved. Thus, a large oil engine crankcase, when made in aluminium alloy, weighed 284 lb.; the crankcase when cast in Elektron weighed only 168 lb., i.e. about 60 per cent of the former weight. In another instance it was found possible to reduce the weight of a petrol engine crankcase from 210 lb. for aluminium alloy to 128 lb. in Elektron, i.e. about 61 per cent. Automobile gear-box castings when made in magnesium alloy are also about 60 per cent of the weight of aluminium alloy ones.

The use of magnesium alloys for *brake drums* and *brake shoes* also enables an appreciable reduction in the unsprung weight of the chassis to be effected; similarly in the case of back axle casings. When used for brake drums it is necessary to employ cast-iron liners for the friction wear surfaces. The alloy drums are usually ribbed for cooling purposes and, on account of the much better heat conductivity as compared with cast iron, the friction heat is dissipated more readily. The smaller castings such as brake parts, brackets, covers, motor cycle crankcases, etc., are made by the gravity die-casting process.

The *wheels* of commercial vehicles can be made of magnesium alloy and enable a marked saving in the unsprung weight. Thus, in the instance of the Zipper wheel for commercial vehicles fitted with pneumatic tyres, the body is made as a one-piece casting and the wheel is only 40 to 50 per cent of the weight of the equivalent size of steel wheel; moreover, it has a much better heat conductivity. These wheels have given satisfactory results in service over distances of 100,000 miles in individual cases. As an example of the saving in weight per wheel with magnesium alloys, it may be mentioned that the weights of rear wheels, for the same commercial vehicle, in steel, aluminium alloy and Elektron, were 246, 150 and 92 lb. respectively.

In the *aircraft industry* the application of magnesium alloys is of greater importance than in any other field, since weight reduction is a primary consideration in aircraft construction and aircraft engines. In this field, magnesium alloys of high specific tenacity are used in the

form of forgings, castings, extrusions and fabricated sheet metal parts wherever possible.

The possibility of using magnesium alloy aircraft wings is at present under consideration and preliminary tests have been made by the American Bureau of Aeronautics and the Dow Chemical Company upon a complete full-scale aeroplane wing outer panel made entirely of high-strength magnesium alloys (Dowmetal J.I. and Z.I.) weighing about 179 lb. as compared with 220 lb. for the corresponding aluminium alloy panel. The tip deflection of the magnesium alloy wing, under
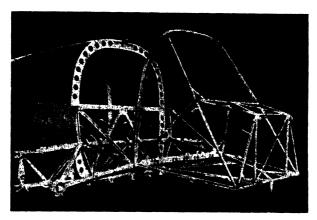
Fig. 53. Monocoque Rear Fuselage in Elektron Sheet and Section

100 per cent proof load, was about 22 per cent greater than for the aluminium one under the same load; this agrees with the theoretical results that the deflections are inversely proportional to the weights of these metals. The lighter wing had less torsional rigidity and more torsional deflection, but it was found that there was little change in the critical flutter speed. If the flight tests on such wings prove satisfactory, a saving of about 20 per cent in the structure weight will be possible, so that the load-carrying capacity of aircraft can be increased.

Airscrew blades, as previously mentioned, are made from wrought alloy forgings. Owing to the low elastic modulus of these alloys the resulting high elastic hysteresis gives a considerable damping capacity so that airscrew vibrations are prevented from reaching a dangerous amplitude. The blades of variable-pitch airscrews are now almost invariably made of magnesium alloy; blades up to 6 ft. in length are now in service.

The alloys used for airscrew blades have a specific tenacity of 12 to 14, an elastic modulus of about 5·6 to 6·0 million lb. per sq. in. and a proof stress of 12 to 15 tons per sq. in. A typical finished blade measuring 6 ft. in length weighed about 45 lb.; another of 5 ft. 2 in. in length, 36 lb.

Castings used in airframe construction, e.g. brackets, landing

FIG. 54. ELEKTRON SHEET FUEL TANK PRESSINGS MADE ON A
DROP HAMMER
(*Flight* copyright)

gear parts, brake shoes, tail wheels, dashboard mountings and brackets, are also made of this alloy.

Fabricated parts such as petrol tanks, seat frames, ribs, rudder and aileron frames, door frames, etc., are frequently made from magnesium alloy sheet, extruded sections and tubing, by riveting or welding methods.

Typical fuel tanks made from Elektron sheet are much lighter than those of aluminium alloy and, if suitable precautions are taken in

regard to the welding procedure and protection against any possible
action by leaded fuels, are entirely satisfactory.

In connection with the weights of aircraft fuel tanks a cylindrical
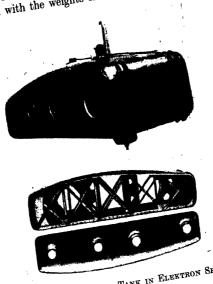
FIG. 55. AIRCRAFT FUEL TANK IN ELEKTRON SHEET

FIG. 56. SECTION OF AIRCRAFT ELEKTRON SHEET FUEL TANK

welded Elektron one with domed ends of capacity 230 gal. weighed
only 31·5 lb. In another example of 900 gal. it weighed 55 lb.

In regard to the *riveting* of aircraft sheet magnesium alloy parts

it is not necessary to use hot rivets. Suitable rivets of 5 per cent magnesium-aluminium alloy, known as MG.5, are now used cold and, owing to the fact that the added magnesium gives the rivet metal a similar electro-chemical potential to that of Elektron sheet metal, no corrosion occurs between the rivet and sheet metal; another 7 per cent magnesium-aluminium alloy known as MG.7 is also used for rivets.

In *aircraft engine construction*, magnesium cast alloys are used for crankcases, supercharger casings, main bearing caps, valve gear oil-tight caps, camshaft and timing gear covers, oil transfer pipes, oil filter casings, vacuum pump housings, air intakes, magneto-drive housings, and numerous other lightly stressed parts for covers, ducts, brackets,

FIG. 57. MAGNESIUM-ALLOY AIRCRAFT ENGINE BEARER

etc. Aircraft engine cowling and fairings are frequently made of sheet magnesium alloy and are pressed or otherwise fabricated to shape.

Another important application of magnesium alloys is that of *aircraft engine bearers*. Fig. 57 illustrates one of a pair of such bearers made in Elektron for supporting an engine weighing about 1600 lb. Each bearer weighed only 26 lb. The front and rear trunnion attachments are shown, respectively, at F and R. When fitted to the nose of an aircraft an inclined tubular strut member is attached between the lug S and the bulkhead frame of the machine, whilst the end T is secured direct to a fitting in the upper part of the bulkhead. The forged Elektron alloy has a proof and (ultimate) tensile stress of 12 and 20·5 tons per sq. in., respectively, with 13 per cent elongation.

The *landing wheels* of many modern aircraft are made of cast magnesium alloy; thus the Dunlop aero wheels employ Elektron castings for the complete spoked wheels.

In general and industrial engineering where lightness combined with good mechanical strength is required—as for portable units and parts—magnesium alloys represent about the lightest solution. Typical instances of their uses include the castings for portable electric and pneumatic tools, the castings of road rammers of the petrol engine-operated type, portable electric lamps for mine use, certain moving

parts of textile machinery, deep-sea diving apparatus, portable petrol-electric plant for generating electricity and wireless transmitters, cutting-off mechanism of cigarette machinery, etc.

In electrical engineering also, these alloys are finding favour for light dynamo and motor castings, trolley-bus gear, switchgear, etc.
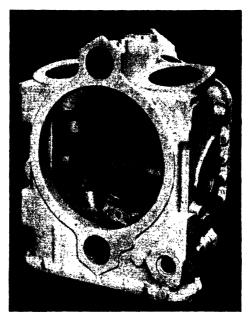
FIG. 58. AIRCRAFT ENGINE TIMING GEAR CASTING
(*Magnesium Castings & Products, Ltd.*)

Welding Magnesium Alloys

As mentioned previously, certain alloys such as the magnesium-manganese group are readily weldable, and these are employed for sheet metal fabrication purposes. Similarly, several of the wrought and cast ·alloys can be welded satisfactorily by the oxy-acetylene method, using suitable welding rods and fluxes. As the latter are highly corrosive it is important, after welding, to remove all traces of the flux by washing and brushing, followed by immersion or thorough scrubbing in a bath consisting of 15 per cent of potassium dichromate in water (used hot), and then in another bath of 10 to 15 per cent of strong nitric acid in cold water to which a small percentage of potassium dichromate in hot water is added until the bath turns dark brown in colour.

In connection with the welding of castings these should be pre-heated to 250° C. to 300° C., at which temperatures white paper rubbed on the metal will turn a light chocolate colour.

With *sheet metal welding*, lap welds by the oxy-acetylene process are not very satisfactory in view of the difficulty in removing all traces of the corrosive flux from between the lapped portions. For thin gauge sheet or sections the butt-welding method is recommended; if the edges can be flanged before welding a stronger junction is

FIG. 59. INDUCTION BELT CASTING FOR AIRCRAFT ENGINE
(*Magnesium Castings & Products, Ltd.*)

obtained. Usually, in aircraft practice butt welding is employed for all sheet metal gauges down to No. 24 (0·022 in.); for thicknesses greater than 0·125 in. the edges should be bevelled to 45° so as to obtain a total included angle of 90° for the Vee to be filled with welding metal.

It is recommended that, wherever possible, welds in sheet metal should be heated to 270° C. to 320° C. and hammered all along. This method is usually followed during the welding process until all the welds are complete on the part under construction. It is then followed by the chromating process previously mentioned.

Special welding fluxes and welding rods for magnesium alloys of different compositions, including the Elektron series, are usually supplied by the manufacturers of these alloys and by the British Oxygen Company, London; the same firms also publish fully detailed

literature on welding technique and procedure relating to the alloys in question.

Electric spot and resistance welding methods are also possible with Elektron alloys for sheet metals, but castings do not spot-weld satisfactorily. Copper electrodes are used for spot welding, but these require occasional cleaning in order to prevent spluttering of the metal during the welding operation. In connection with the strength of welded sheet metal joints by the oxy-acetylene process, the results of
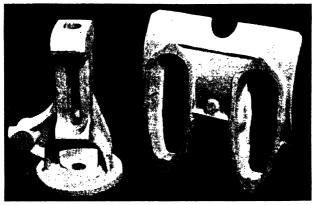
Fig. 60. (*Left*) GUIDE BRACKET, AND (*right*) ROCKER GEAR COVER CASTINGS FOR AIRCRAFT ENGINES

(*Magnesium Castings & Products, Ltd.*)

tests* on rolled Elektron taken across the line of weld showed that unhammered welds gave from 40 to 60 per cent of the strength of the unwelded sheet, whereas hammered welds gave from 75 to 90 per cent.

Machining Elektron Alloys

These, in common with other light magnesium alloys, have free-cutting qualities and are superior in machining properties to aluminium alloys. In order to obtain full advantage of the high cutting speeds at which Elektron may be machined, it has been necessary to develop new designs of machine tools allowing spindle speeds up to 5000 r.p.m., so that Elektron parts may be machined at speeds of 4500 ft. per min. without tear or drag. Apart from the high cutting speeds possible, the power required for machining is less than with any other metal.

Generally, Elektron is machined without employing coolants. Turning, boring and drilling, milling and screw-cutting operations

* "Welding Magnesium Alloys," A. Eyles, *The Machinist*, 3rd August, 1935.

require no lubricants, and only in some exceptional cases, e.g. drilling
deep holes, cutting small screw threads, finish-turning and grinding
operations, a suitable cooling medium, such as thin oil or crude
kerosene, is required, the latter being used exclusively for grinding.
Where the stock is removed in the form of very fine chips or powder,
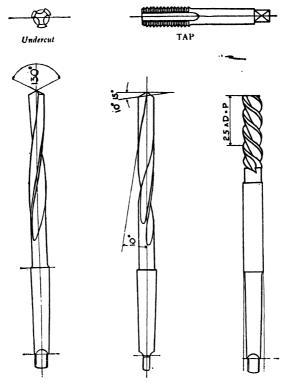
FIG. 61. TWIST DRILLS, REAMER, AND TAP FOR MAGNESIUM ALLOYS

thin oil is recommended to prevent the chips from flying about or
igniting.

The forms of cutting tools recommended for Elektron alloys are
illustrated in Figs. 61 to 63.

Ordinary high-speed steel tools are quite suitable. During turning
operations the degree of heating depends on the rate of feed, the heat
developed being conducted away better with larger feeds than with
smaller ones. For drilling operations, the use of *long lead spiral drills*
(Fig. 61) is recommended. The point angle should be 130° and spiral
angle 10°. Flat drills can also be used. In place of counterbores boring-

bar cutters are employed for holes up to 1 in. in diameter. A further advantage in the use of boring bars is the improved chip removal, although, with deeper bores, it is desirable to apply compressed air both for cooling and removing chips.

Milling cutters (Fig. 62) should be used with a cutting speed of
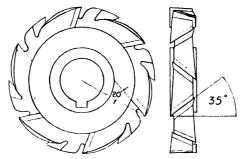
FIG. 62. SIDE AND FACE CUTTER FOR MILLING MAGNESIUM ALLOYS
(*F. A. Hughes, Ltd.*)

900 ft. per min. and a feed of 12 in. per min. Heavy cuts should be taken, but the cutters must be kept sharp. 24-in. diameter inserted blade cutters have been used on crankcase milling with a cutting speed of 4900 ft. per min. and a table feed of 4·6 ft. per min.
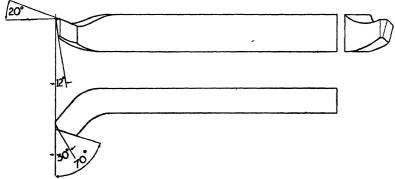
FIG. 63. HEAVY CUT TURNING TOOL FOR MAGNESIUM ALLOYS
(*F. A. Hughes, Ltd.*)

For *turning operations* the tool shown in Fig. 63 is recommended. This has a top rake of 20°, clearance angle of 12° and cutting angle of 58° to 60°. The cutting speed for heavy cuts is 900 ft. per min.; depth of cut, $\frac{5}{16}$ in. and feed for roughing, 0·02 in. per rev. For finishing purposes tools with less rake should be used and a feed of

0·01 in. per rev. It should be pointed out that normal shapes of cutting tools for aluminium alloys will give satisfactory results, if kept sharp.

For *tapping purposes* the three flute tap (Fig. 61) gives good results if the cutting edges are kept sharp.

For *reaming purposes* a 45° spiral cutter, undercut (Fig. 61), is recommended.

Band-saws should have 5 teeth per inch.

For *grinding Elektron alloys* special wheels are supplied by The Carborundum Company, Ltd., and the Norton Company. Grinding speeds of 800 to 1000 ft. per min. are recommended for the grinding wheel, and for circular ground alloy parts a speed of 80 ft. per min. for the work itself.

Polishing should be carried out with glass or flint paper. Emery paper or cloth should not be used ; the surfaces should be protected with lanolin if the parts are to be stored.

Elektron alloy parts may be cleaned of dirt or oil with petrol. Surface deposits are usually removed by dipping in dilute acid or alkali baths and afterwards washing thoroughly in hot water.

CHAPTER V

COPPER AND ITS ALLOYS

COPPER is used extensively in engineering and industry both by itself and in the form of alloys with other metals as in the brasses, bronzes, bearing metals, nickel-silvers, etc.

Copper occurs in the metallic form in nature, in crystalline form, e.g. in large masses near Lake Superior, U.S.A., and some Siberian mines. It is also represented in some 240 copper bearing minerals as oxides, sulphides, carbonates, arsenates, etc. Among these mineral ores are *Malachite* ($CuCO_3.Cu(OH)_2$), *Copper Glance* (Cu_2S), *Ruby Ore* (Cu_2O), *Azurite* ($2CuCO_3.Cu(OH)_2$), and *Copper Pyrites* ($Cu_2S.Fe_2S_3$).

The processes of extraction of the copper from its ores vary with the nature of the latter, but the crude copper obtained, on account of its blistered appearance, is termed *blister copper*. This impure copper is refined by a subsequent remelting process in a reverberatory furnace having an oxidizing atmosphere and finally by an electrolytic process which yields ingots of a high standard of purity.

In engineering practice three principal grades of copper are employed, namely—

(1) *H.C. (High Conductivity) Copper.* This is of 99·9 per cent purity and is used for electrical purposes and where high thermal conductivity is required. B.S.S. 1036 and 1037 deal with raw coppers of this group.

(2) *Refined Copper.* This has very small amounts of impurities, usually sufficient to prevent it from quite conforming to the conductivity standard of H.C. copper. It has a wide range of industrial uses. B.S.S. 1038, 1039, and 1040 deal with three qualities of differing purities in this group.

(3) *Arsenical Copper.* This contains up to 0·5 per cent of arsenic. It is widely used for plates, tubes and sheets in engineering work.

When these coppers contain small percentages of oxygen they are known as "*tough-pitch*" coppers. For certain purposes, however, the inclusion of oxygen is a disadvantage, e.g. for welding and tube manufacture, so that oxygen-free copper or *deoxidized* copper is then employed.

Cathode copper is another commercial form obtained by electrolytic refining. As the crystal structure is not suitable, as a rule, for general working, this grade is employed for alloy making.

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Copper powder is another commercial product obtained by electrolysis under specially controlled conditions and also by pulverizing and grading; it is used for moulding and other purposes.

Lithium-copper. Lithium has been found to be an excellent deoxidizing and refining agent for copper, the commercial lithium-copper product being high in density and electrical conductivity. It has a relatively low lithium-calcium content, usually below 0·01 per cent; this tends to protect the copper against subsequent oxidation.

Lithium-copper, although not yet of commercial importance, has the same melting and casting procedure as ordinary copper, but can be annealed at considerably higher temperatures than oxygen-containing copper: it can be bright-annealed conveniently and satisfactorily.

Properties of Copper

Copper in the clean polished condition is a lustrous "copper-red" metal possessing excellent malleability and ductility; the presence of impurities, however, diminishes the two latter properties.

When exposed to the air in the presence of moisture and carbon dioxide it becomes coated with a greenish basic carbonate which, under normal atmospheric conditions, acts as a protection against further corrosion; for this reason and also on account of its decorative green patina effect copper is often used for sheathing the domes of buildings, etc. It is practically unaffected by caustic alkalis, sea and other waters, and is used for the plating or sheathing of wooden ships.

It is strongly attacked by nitric acid but only very slowly by dilute hydrochloric and sulphuric acids in the absence of air; ammoniacal solutions also attack copper.

Polished copper when exposed to clean dry atmospheres may acquire an invisible protective film of cuprous oxide (Cu_2O) which increases its resistance to subsequent attack by contaminated atmospheres.

Copper is an excellent conductor of heat and electricity, being second only to silver in these respects—as shown by the comparative values given in Table 45.

Applications of Copper

On account of its high thermal conductivity copper is employed for locomotive fire-box plates, radiator elements, domestic boilers, moulds for casting metals (also for bottom plates), refrigerator tubes, coils and vessels, domestic cooking utensils and kettles, etc. It has also been employed for the cylinder heads of internal combustion engines

in special instances on account of its much better heat conductivity and dissipation qualities as compared with aluminium.

TABLE 45

THERMAL AND ELECTRICAL CONDUCTIVITIES OF COMMERCIALLY PURE METALS (20° C.)

Metal	Relative Thermal Conductivity (Copper = 100)	Relative Electrical Conductivity (Copper = 100)	Coefficient of Linear Expansion per °C. at 20° C. × 10⁻⁶
Silver . . .	108	106	19
Copper . . .	**100**	**100**	**16·6**
Gold . . .	76	72	14
Aluminium . .	56	62	23
Magnesium . .	41	39	26
Zinc . . .	29	29	30
Nickel . . .	15	25	13
Cadmium . . .	24	23	31
Cobalt . . .	17	18	12
Iron . . .	17	17	12
Steel . . .	13–17	13–17	12
Platinum . . .	18	16	9
Tin	17	15	21
Lead . . .	9	8	28
Antimony . .	5	4·5	11

The high electrical conductivity of this metal has led to its universal adoption for electrical conductors, e.g. windings of dynamos, motors, transformers and other coils, for bus-bars, switchgear parts, electric power transmission cables, telegraph and telephone wires and cables, electrodes for welding machines and furnaces, house wiring, lightning conductors, etc.

The metal is readily fabricated by cold-rolling, drawing, pressing, spinning and coining, and by extrusion, forging and stamping at elevated temperatures. It is easy to machine and can readily be soldered, brazed and welded.

Brazing and Welding

Hydrogen Furnace Brazing. Copper is now being used to an appreciable and increasing extent for brazing steel parts such as electrical refrigerators, evaporators, pistons, and check valves.

It is necessary, of course, to employ a reducing atmosphere; hydrogen or a mixture of hydrogen and nitrogen is used for this purpose.

Copper brazing is carried out in the electric furnace at temperatures of about 1150° C., i.e. slightly above the melting point of copper. Owing to the presence of a protective atmosphere, nickel-chromium ribbon resistors operating at high-watt densities can be used for the heating elements.

If two pieces of steel are joined tightly together and a small quantity of copper is placed adjacent to the seam, the whole being heated until the copper melts, it is known that the copper will flow rapidly without flux into the joint and be distributed evenly throughout the contact area by means of capillary attraction. Since capillary attraction aids the process, it follows that the distribution of copper improves with the tightness of the fit. Only a very thin film of copper forms the bond, and when properly applied its cost is almost negligible.

There are two important advantages with this method. Firstly, the steel is annealed in the process by slow cooling in the reducing atmosphere. In this connection, it might be stated that carburized parts may subsequently be hardened by observing certain precautions, and, in general, heat-treating processes may be carried out successfully after brazing, provided the temperatures used do not reach the melting point of copper.

The second advantage is that less pickling or cleaning is required. The work comes from the hydrogen furnaces bright, smooth, and clean, with no roughness at the joints or oxidation of the surfaces; in fact, the appearance of the parts is improved by the brazing operation, owing to the cleaning effect of the reducing atmosphere.

Welding of Copper. Copper can be welded satisfactorily by the oxy-acetylene and electric resistance methods if suitable precautions are taken. The high thermal conductivity of copper is a disadvantage in welding since the heat is dissipated more readily from the parts to be welded. Preheating of the parts is generally necessary. The copper employed for oxy-acetylene welding operations is of the deoxidized kind, although tough-pitch copper can be welded satisfactorily by this method. The filler rods are of deoxidized copper and a borax flux is recommended; this acts also as a protective skin over the metal. A neutral flame must be used to obviate oxidization of the copper from the air.

Annealing Temperature

The annealing temperature of copper varies between 200° C. and 600° C., according to the impurities present and the condition of the metal, i.e. upon the amount of cold work it has been subjected to. Work-hardened copper of high purity may be partly softened at

temperatures as low as 120° C., but the minimum softening temperature is usually at least 200° C. For most commercial coppers a temperature of 500° C. is employed, but for heavy sections the furnace temperature may be raised to 600° C. After raising to the annealing temperature it may be cooled in any convenient manner, namely, in air or by water quenching; the latter method facilitates the removal of dirt and scale.

Physical Properties

The following are the chief physical values for commercially pure copper—

Specific gravity, H.C. copper, 8·89.
Specific gravity, rolled or hammered, 8·93.
Weight per cubic inch (cast), 0·31 lb.
Coefficient of linear expansion, 20°–100° C., 0·0000166 per ° C.
        20°–300° C., 0·0000176 per ° C.
        20°–500° C., 0·0000186 per ° C.
Melting point, 1083° C. (1981° F.).
Boiling point, 2325° C. (4217° F.).

The specific heat at normal temperatures is 0·092 C.G.S. units. This value increases with temperature increase, being 0·098 at 300° C.

Latent heat of fusion, 41·7 to 50·46 calories/gramme.
Conductivity, electrical, at 20° C., 1·7241 microhms per cm. cube.
        at 60° F., 1·6942 microhms per cm. cube.

Resistance temperature coefficient

$$R_t = R_o [1 + a_o(t - t_o)]$$

where $a_o = 0·004265$ and t is the temperature at which the resistance is required.

The value of a_o is not constant but varies with the temperature according to the following relation—

$$a_t = \frac{1}{234·5 + t}$$

Mechanical Properties

The strength properties of copper depend upon its condition, i.e. whether cast or cold-worked, and the extent of the working; also upon the nature and amount of impurities or other elements present.

Reasonably pure *cast copper* has a tensile strength of 10 to 11 tons per sq. in., with 25 to 30 per cent elongation (on 2 in.).* When *rolled*

* Mechanical strength values given by the Copper Development Association

or forged, followed by annealing, the tensile strength is increased to 14 to 16 tons per sq. in., with 50 to 60 per cent elongation.

For *cold-rolled copper* in sections greater than ⅛ in., the tensile strength varies from 20 to 26 tons per sq. in., with reduced ductility, i.e. with 5 to 20 per cent elongation. The Brinell hardness is 80 to 100 as compared with 45 to 55 for the annealed and 40 to 45 for the cast metal.
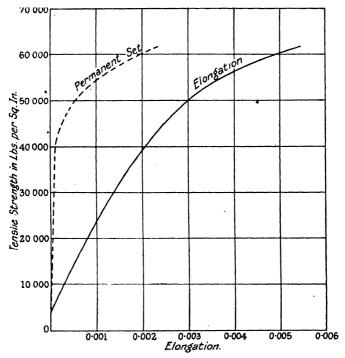
FIG. 64. STRESS-STRAIN CURVE FOR HARD-DRAWN COPPER WIRE

Heavily worked copper such as the wire has a tensile strength of 25 to 30 tons per sq. in. with 5 to 1 per cent elongation. In this connection the actual strength value depends upon the diameter of the wire; thus, in the British Standard Specification for hard-drawn copper wire the minimum tensile strength ranges from 22·9 to 29·5 tons per sq. in., as the diameter varies from 0·4 in. to 0·064 in.

The stress-strain curve for hard-drawn copper wire is shown in Fig. 64, from which it will be observed that there is practically no straight portion of the curve and therefore no definite elastic limit or yield point.

The *modulus of elasticity* for hard-drawn copper in wire, rod or sheet form is 18×10^6 lb. per sq. in.

The *modulus of torsion*, or rigidity, is from 6 to 7×10^6 lb. per sq. in.

The *limit of proportionality* of stress-to-strain of copper *in compression* is approximately equal to the value in tension. Annealed copper will withstand a very large amount of deformation in compression without cracking at the edges; thus, reductions in thickness of 10 to 1 may be made without difficulty.

The yield point of copper, as previously mentioned, is very indefinite so that it is usual to refer to *the proof stress* which is just sufficient to produce a permanent set equal to 0·10 per cent of the gauge length.

The fatigue or *endurance limit* of annealed copper for 50 million reversals is $\pm 4\frac{1}{2}$ tons per sq. in.

Effect of Cold Work on Mechanical Properties

Copper can be hardened or "tempered" by subjecting it to varying amounts of cold work, e.g. cold rolling or hammering. The general effect of this treatment is to harden the metal as shown by the increased Brinell value, to increase its tensile strength and proof stress (0·10 per cent) and to reduce the percentage elongation.

These effects are illustrated by the results given in Fig. 65.

Creep and Strength at Elevated Temperatures

Copper possesses a good creep resistance and hard-drawn copper wire,[*] subjected for almost a year at ordinary temperatures to a load equivalent to 75 per cent of its tensile strength, showed a steady rate of creep, after the initial period, of only 5×10^{-7} per day. As the temperature of copper is increased the tensile strength falls progressively and both the elongation and reduction of area increase continuously. The results of some tests[†] upon copper previously reduced 25 per cent in cross-sectional area by cold rolling are given in Fig. 66. These results show that no brittle range occurs, so that it can be inferred that copper possesses ideal hot-working properties.

Effect of Other Elements on Copper

The impurities which may occur in commercial copper include arsenic, antimony, bismuth, oxygen (as cuprous oxide), lead, nickel, sulphur, tin, zinc, silver.

[*] British Non-Ferrous Manufacturers Research Association Report No. 449.
[†] W. B. Price, A.S.T.M., A.S.M.E., "Symposium on Effect of Temperature on Metals," 1931.

When the *oxygen content* is less than about 0·1 per cent it has only a slight effect on the electrical, mechanical and physical properties; in rather greater proportions it tends to cause brittleness.
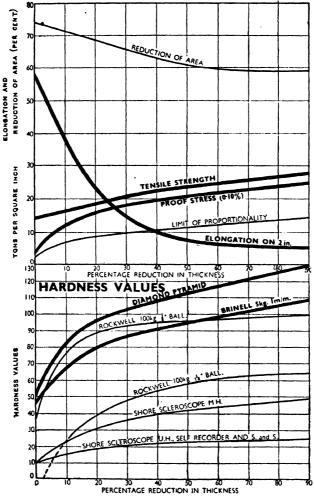
FIG. 65. EFFECT OF COLD ROLLING ON THE STRENGTH AND HARDNESS OF H.C. COPPER STRIP

(*C.D.A.*)

Bismuth in copper reduces the tensile strength and causes red-shortness.

Arsenic in amounts up to about 0·5 per cent increases the tensile

strength and toughness and for this reason arsenical copper is widely used in engineering, except for electrical purposes. The British Standard Specification No. 200 for Copper specifies from 0·3 to 0·5 per cent of arsenic.

Additions of up to 0·5 per cent arsenic improve the tensile strength of annealed copper by somewhat less than 1 ton per sq. in. and only
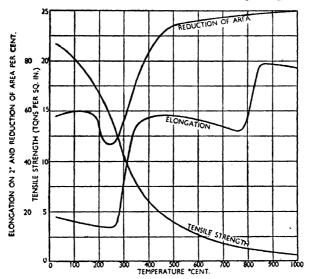
FIG. 66. PROPERTIES OF COPPER AT ELEVATED TEMPERATURES
(*C.D.A.*)

very slightly increase its hardness values. In the cold-worked condition, however, the effect of arsenic is reflected in quite an appreciable increase of strength and of hardness, e.g. after cross-sectional reductions of 50 per cent, the tensile strength of arsenical copper is up to 2 tons per sq. in. greater and Brinell hardness 15 points higher than with H.C. copper.* In addition to giving general toughening or strengthening, arsenic also slightly raises the endurance limit as determined by fatigue testing.

Arsenic raises by about 100° C. the temperature at which softening upon annealing first occurs, and also slightly improves the retention of strength at elevated temperatures. These two features have been responsible for the adoption of arsenical copper for a large number of applications, such as *locomotive fire-boxes.*

The electrical and thermal conductivity of copper is adversely

* Copper Development Association.

influenced by the presence of arsenic, and with an arsenic content of 0·4 per cent the conductivity values may be less than half the corresponding H.C. copper values. In comparison with alloys of most other metals, however, these values are still of a high order.

Silver in amounts up to 0·1 per cent raises the temperature required for initial softening upon annealing, but has a negligible influence upon the conductivity values. These copper-silver alloys are employed for parts which require hardness with high conductivity at somewhat elevated temperatures where ordinary work-hardened H.C. copper would be softened. A typical application is in connection with electrical switchgear contacts. It is also employed for parts that have to be soft soldered without the risk of softening the metal, e.g. radiator gills on tubes.

Cadmium, a whitish metal similar to zinc with a tensile strength of only 4 to 5 tons per sq. in., when added to copper in an amount of 0·8 to 1·0 per cent increases the tensile strength by about 50 per cent with a corresponding reduction in the electrical conductivity of only about 15 per cent (in the work-hardened condition). With the addition of 0·9 per cent of cadmium it is possible to produce the smaller sizes of wire with a tensile strength of about 45 tons per sq. in. and an electrical conductivity of about 85 per cent of the I.E.C. standard for annealed copper.

Cadmium-copper wires of this class are used for telegraph and telephone line purposes; for trolley wires the larger sections of wire employed have a minimum tensile strength of 28 tons per sq. in. and 89 per cent electrical conductivity. This alloy is also used for high tensile overhead electrical transmission lines and it is claimed to be superior in certain important qualities to steel-cored aluminium cable.*

Other Copper Strengthening Elements

The tensile strength and hardness of copper are improved by the addition of small percentages of a number of different elements including tin, zinc, nickel, and aluminium. The effect of each of these elements as well as cadmium upon the strength and hardness is illustrated clearly in Figs. 67 and 68. The greatest improvement in strength and hardness is that due to tin and aluminium ; zinc and nickel up to 8 per cent do not affect these qualities appreciably.

The copper-zinc alloys form the well-known group known as the *brasses*.
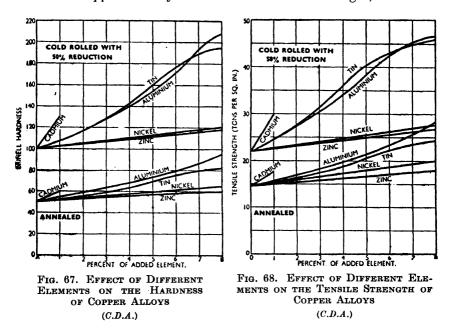
The copper-tin alloys are generally termed bronzes, although many

* "Cadmium-Copper Conductors," G. W. Preston, *Electrical Review*, 15th March, 1935.

other alloys having no tin at all are now referred to as bronzes, e.g. copper-aluminium alloys are called *aluminium bronzes*. It should be noted that *manganese bronze* is a high tensile brass containing a small amount of manganese.

Beryllium is another strengthening element, to which reference is made later in this chapter.

Nickel, in small amounts up to about 10 per cent, in certain copper-zinc and copper-tin alloys increases their tensile strength, hardness

FIG. 67. EFFECT OF DIFFERENT ELEMENTS ON THE HARDNESS OF COPPER ALLOYS

(*C.D.A.*)

FIG. 68. EFFECT OF DIFFERENT ELEMENTS ON THE TENSILE STRENGTH OF COPPER ALLOYS

(*C.D.A.*)

and ductility whilst at the same time providing greater resistance to corrosion at normal and elevated temperatures.

Typical Alloys of Copper

Before dealing in rather more detail with the common alloys of copper it is of interest to give a summary of the principal alloys used in automobile and aircraft construction. The compositions, mechanical properties, B.S. specifications and applications of these are given in Table 46.*

* "Copper and Its Alloys in Automobile Design," D. P. C. Neave, *Proc. Inst. Autom. Engrs.*, February, 1937.

TABLE 46—COPPER ALLOYS USED IN ENGINEERING

Alloy	Composition: Approximate Average per cent by weight					Approximate Comparative Mechanical Properties			British Standard Specification No.	Typical Automobile Uses
	Copper	Zinc	Tin	Lead	Others	Tensile Strength Tons per sq. in.		Elongation per cent Annealed		
						Annealed	Hard*			
1. High conductivity copper	99·90 min.					14	25	45	128 156	Windings of dynamo, starter, coil and electrical accessories. Wiring. Some radiator films, tubes and fins. Gaskets, pipe-lines.
2. Arsenical copper	99·20 min.				0·4 Arsenic	14·5	26	45	4 T.7, T.51 2 B.15	Some pipe-lines and gaskets.
3. 85/15 gilding metal or red brass	85	15				19	31	57		Corrugated tubing for flexible pipe-line inserts, thermostat bellows. Lockheed hose nipples.
4. Cartridge brass	70	30				22	36	70	267	Shells, films and lock-seamed tubes for radiators. Pipe-lines for central lubrication. Brake lining rivets. Carburettor floats.
5. 65/35 brass	65	35				22	37	65	266	Intermediate alloy for sheet and strip for cold presswork.
6. "Basis" brass	63	37				23	38	60	265	Hub-covers, lamp bodies and other pressed sheet metal; some cold-headed screws and bolts.
7. Leaded basis brass	63	rem.		0·5–1·5		23	37	50		Side plates and toothed wheels for instruments. Engine and chassis number-plates.
8. Hot stamping brass	58	40·5		1·5		25		30	218	Hot brass stampings for control levers, taps, small brackets, etc.
9. Free cutting brass	58	rem.		2·75		25		25	249	Spindles, nuts, windscreen frames and other parts made from extruded brass bar. Float-chamber toggles.
10. Manganese-bronze	60	36			Total of Fe, Mn, Al, Sn, Ni, 4 approx.	30–40		22	250 268	Hot stampings and extruded rod for high-tensile brass nuts, bushes, selector forks, etc. Castings for pump rotors, etc.
11. Aluminium-bronze	90				10 Al with 1 to 3 Fe or Mn for castings	35–40		30	D.T.D. 174 160	Die-cast selector forks, etc. Some worm wheels, cylinder-head castings, valve-seat inserts.
12. Admiralty gunmetal	88	2	10			17		20	383	Miscellaneous sand-castings for marine fittings, pump casings, etc.
13. Phosphor-bronze castings	89·5		10 min.		0·5 Phos.	18		4	2 B.8	Gudgeon-pin and other bushes. Some valve guides. Worm wheels.
14. Wrought phosphor-bronze	rem.		3·5–7·0		0·1 Phos. approx.	24	30–60	65	334, 407 D.T.D. 78A	Cold-worked strip or wire for electrical and other springs; strip or tube for medium-duty bearings; some valve guides.
15. Copper-lead bearings	55–75			rem.		8		15	D.T.D. 229	High-duty big-end and main bearings.

* After 50 per cent reduction of cross-sectional area by cold working, except No. 14.

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The Brasses

The alloys of copper and zinc are more generally referred to as "brasses," but special commercial brasses also contain small amounts of other elements, such as nickel and lead, which give them certain advantages in particular applications.

Molten copper will dissolve zinc in all proportions, namely, up to
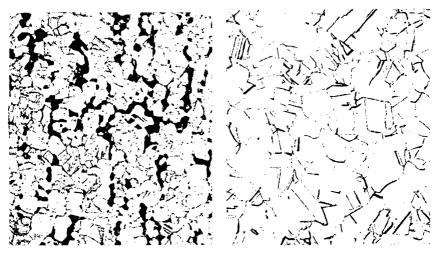
FIG. 69. ROLLED AND ANNEALED
YELLOW METAL (61% C). × 100
(*C.D.A.*)

FIG. 70. ROLLED AND ANNEALED
70/30 BRASS. × 100

nearly 100 per cent zinc, with suitable precautions in regard to the stirring, and will give a uniform liquid solution.

This uniform solution can also be obtained in the case of brass when solidified, provided the zinc content does not exceed 37 per cent. The resulting alloy consists of crystals of a uniform solid solution of zinc dissolved in copper. This is known as the *alpha solid solution*. The alpha brasses coming within this category include the *Gilding Metals* (6 to 20 per cent zinc); *Cartridge Brass* (30 per cent zinc); *Yellow or Muntz Metal* (40 per cent zinc); *Dutch Metal* (20 per cent zinc); *Red Brass* (15 per cent zinc) and other alloys known by trade names.

There is another group of brasses, known as the *alpha-beta* ones, having a higher zinc content and containing a second zinc-rich constituent; namely the *beta solid solution*, occurring as distinct crystals of reddish colour. The resulting duplex structure is known as an alpha-beta brass.

The equilibrium diagram* for these two types of brasses is given in Fig. 72, which shows the melting points of the copper-zinc alloys containing up to 50 per cent zinc; it shows also at the various temperatures whether *alpha* or *beta* crystals, or both, are present. It should be added that whilst the equilibrium diagram in Fig. 72 is sufficiently correct for general explanation purposes it appears to require slight modification as a result of more recent research. Further, in the case of zinc-rich brasses, e.g., 37 per cent zinc or 63/37 brass, it is necessary
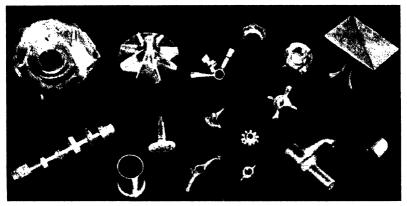
FIG. 71. EXAMPLES OF HOT BRASS STAMPINGS FOR AUTOMOBILE, BUILDING, AND GENERAL ENGINEERING PURPOSES
(*C.D.A.*)

that the cooling should be slow enough to give the crystals time to rearrange their form.

The alpha brasses possess good tensile strength combined with considerable ductility when cold, making them suitable for producing sheet, strip, tube, wire, etc.

The comparative mechanical strength properties of these brasses in the wrought condition are shown in Fig. 73;† the lower curve indicates the strength values of these brasses when annealed.

The alpha-beta brasses when cold contain hard *beta* crystals which give increased tensile strength but reduce the ductility. When heated, however, the presence of the *beta* crystals renders the brass plastic over a wide range of temperature, so that brasses containing 39 to 43 per cent of zinc are easily worked by hot-rolling, extruding or hot stamping at temperatures from 600° to 800° C.

* "Copper and Its Alloys," F. A. Fox, *Machinery*, 19th May, 1938.
† *Brasses and Other Copper-Zinc Alloys*, Pub. of Copper Development Association.

The *alpha brasses*, on the other hand, retain high strength in compression at elevated temperatures, and therefore require greater power to hot-work them; the purer alpha brasses are now hot-rolled com-

FIG. 72. EQUILIBRIUM DIAGRAM
OF COPPER-ZINC ALLOYS
(*C.D.A.*)
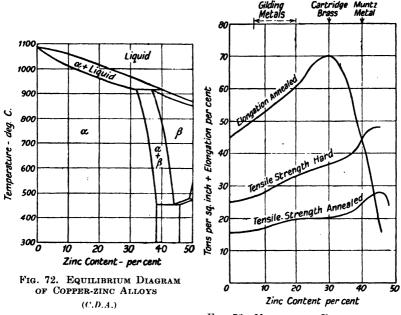
FIG. 73. MECHANICAL PROPERTIES OF
COPPER-ZINC ALLOYS
(*C.D.A.*)

mercially at somewhat higher temperatures than the alpha-beta ones and with more powerful mills.

Physical Properties of Brasses

The specific gravity of copper-zinc alloys varies from 8·93 for pure wrought copper, down to 8·28 for the 50 per cent zinc (50/50) alloy. For other intermediate alloys the specific gravity is approximately proportional to the zinc content.

The average coefficients of thermal expansion per deg. C. from 25° to 100° C. of typical brasses and for H.C. copper are as follows—

80/20 gilding metal	.	.	.	0·000018
65/35 brass	.	.	.	0·000019
60/40 brass	.	.	.	0·000020
H.C. copper	.	.	.	0·000017

The coefficients increase with higher temperatures, being 10 per cent higher for the range 200° C. to 300° C.

The specific heat (average) of copper-zinc alloys at normal temperatures is 0·092 C.G.S. units.

The thermal conductivity of H.C. copper is 0·92 to 0·94 C.G.S. units at 20° C. When additions of other elements are made to H.C. copper its conductivity values are reduced. Thus zinc additions—as in brasses—reduce both the electrical and thermal conductivities. For example, the conductivities of 95/5 gilding metals are about 55 per cent to 60 per cent of the H.C. copper value.

The 70/30 cartridge brass, 65/35 brass and 60/40 yellow brass all have a somewhat similar electrical conductivity, namely, about 27 per cent, and a thermal conductivity of about 30 per cent of the corresponding H.C. values.

Season Cracking

Many of the alloys of copper—notably the alpha and high tensile brasses—are liable, under certain conditions, to develop surface cracks, either during manufacture or when stored. This defect, known more commonly as "season cracking," occurs with cold-worked metals, but never with annealed or cast alloys.

Microscopic examination of the cracks reveals that these occur between and never across the crystals, a fact which indicates that they are caused by internal stresses—tensile or compressive—which are ultimately relieved by the springing apart of the metal at its weakest place, namely, across the crystal boundaries.

Season cracking often occurs with pressed or stamped sheet metals, rods and tubes fabricated by cold-working processes. Such cracks may not, however, develop until long after manufacture, but can be accelerated if the parts are subjected to heating of an uneven or rapid nature. Another cause is when articles are soldered; then cracks may occur due to the temperature of the molten solder. Yet another cause of accelerated cracking is that of chemical action or corrosion. Typical agents causing cracks in internally stressed alloys include ammonia salts, sulphur dioxide, oil and mercurous nitrate. The latter chemical is particularly effective and it is often employed as a means of testing cold-worked articles, such as pressings, for such cracks; if the latter do not occur after immersion of the article it is generally assumed that similar parts will remain immune under normal usage conditions. The design of the dies used for sheet metal pressings has a considerable influence on the production or absence of seasonal cracking tendencies, the general aim being to prevent severe internal stresses from occurring

and to relieve ordinary stresses in multiple press operations by annealing. Annealing relieves stresses in cold-worked articles and season cracks are thereby prevented.

Since the strength properties of many copper alloys are reduced considerably by annealing, this process is sometimes inapplicable as a means of avoiding season cracking, so that in many instances a low temperature heat-treatment method is employed to reduce the season
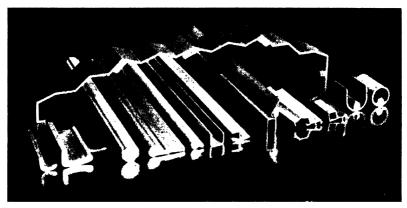
FIG. 74. TYPICAL EXAMPLES OF BRASS AND COPPER EXTRUDED SECTIONS

From left to right, (1) and (2) H.C. copper switch gear units; (3) to (5) Various extruded sections; (6) Interlocking section; (7) to (end) Short lengths from two examples of sections extruded open and afterwards drawn together in a die.

(*C.D.A.*)

cracking tendency. Such treatment, involving maximum temperatures of 200° to 300° C., as a rule not only avoids softening but may even result in a considerable improvement in the limit of proportionality and proof stress of hard-worked alloys.

Notes on the Brasses

As the proportion of zinc is increased in copper-zinc alloys the colour changes from the reddish copper shade to the golden colours of the 95 to 80 per cent copper or gilding metals. When the copper is reduced to about 70 per cent the yellow colour becomes paler, inclining to greenish, and with further reduction in the copper content the yellow colour becomes warmer until with 60 per cent copper the yellow ochre of the "yellow metal" is attained. A further reduction causes a reversion to the golden colour.

Gilding Metals. These 80 to 95 per cent copper alloys have tensile strengths in the hard condition of 26 to 33 tons per sq. in., and elongations

of 49 to 60 per cent (annealed), are very ductile and can be cold-worked to a considerable extent without serious work-hardening. Such metals are used for jewellery and for ornamental purposes as they possess a golden colour. The 97 per cent alloy is used for the caps of cartridges and is known as *cap copper*.

Cartridge Brasses. The 70/30 brass is probably the most important of the alpha brasses and has the greatest elongation values, namely,
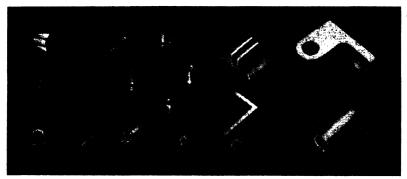
FIG. 75. (*Left*) TYPICAL AUTOMATIC LATHE PRODUCTS MACHINED FROM
EXTRUDED BRASS BARS, AND (*Right*) BRACKETS, ETC., PARTED OFF
FROM LENGTHS OF EXTRUDED BRASS SECTIONS

about 70 per cent (annealed) of the copper-zinc alloys. It is widely employed for cold drawing, pressing and spinning purposes; it can be drawn at about three times the rate of ferrous materials. Further, in deep drawing work two operations will usually give a deeper product than three draws on steel. It is important, in the case of metal for deep drawing, that the iron and lead content should be below 0·05 per cent and bismuth and antimony should be absent.

It has an annealing temperature of 600° C. With the presence of impurities or too high an annealing temperature the grain size becomes relatively large, and individual grains may appear at the surface, giving rise to what is known as "*orange peel*" effect.

Basis Brass. This is probably the cheapest form of brass which is suitable for cold-working. It contains between 61·5 and 64·0 per cent of copper. A typical percentage composition is as follows: Cu, 63·0; Zn, 37. This alloy (annealed) has a tensile strength of 23 tons per sq. in. with 60 per cent elongation; in the hard-drawn state, after 50 per cent reduction of cross-sectional area by cold-working, the tensile strength is raised to 38 tons per sq. in. The 63/36 brass with 1 per cent of lead is more machinable and is used for mass-production

machined parts. The ordinary basis brass is covered by the British Standard Specification No. 265.

Muntz Metal. Sometimes known as *Yellow Metal* this alloy contains 60 per cent copper and 40 per cent zinc. It is used principally on account of its golden yellow appearance for ornamental purposes, such as hand fabricated parts of Oriental origin. It is not suitable for pressing and similar fabricating processes, but owing to the fact that
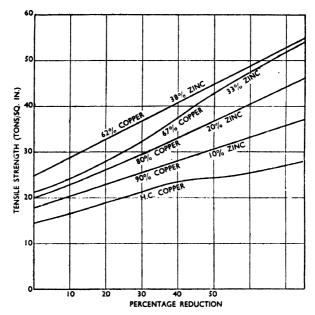
Fig. 76. Effect of Cold Drawing upon Tensile
Strength of Copper-zinc Alloys

at the hot-working temperature it consists entirely of the plastic *beta* phase it is a particularly good hot-working metal.

Hot Stamping Brass. This includes the alpha-beta brasses with about 58 to 62 per cent copper, which are very plastic when hot, and can be stamped, forged or extruded at 600° C. to 800° C. A very wide range of stampings employed in engineering work is made from these brasses. Thus, in automobile work such parts include control levers, pipe junctions, petrol taps, drain plugs, control gear pinions, water pump rotors, wing-nuts, small brackets, etc. The alloy preferred for this purpose contains 1½ per cent of lead to facilitate machining operations. A typical composition, which conforms to the British

Standard Specification No. 218,* has the following percentage compo-
sition: Cu, 58·0; Zn, 40·5; Pb, 1·5.

The average tensile strength is 25 tons per sq. in. with a minimum
of 25 per cent elongation.

Mechanical Properties of Brasses

The tensile strength and other mechanical properties of brasses
depend a good deal upon the condition, i.e. whether cast, forged,
extruded, rolled, or annealed, and upon subsequent cold-work on the
metal. The grain structure of cast metal becomes modified with hot
or cold working and annealing, and the strength is normally greater
in wrought forms.

The values given in Table 47 illustrate the improvement in tensile
strength and hardness, but with reduced ductility, upon 70/30 cartridge
brass in the hard-rolled sheet condition :—

TABLE 47

MECHANICAL PROPERTIES OF CARTRIDGE BRASS (70/30)

Condition	Proof Stress (0·10%) Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation on 2 in. per cent	Brinell Hardness Number
Chill castings (i.e. strip ingots prior to rolling) . . .	6	16	60–70	60
Hard-rolled sheet .	Over 25	30–40	10–15	150–200
Sheet annealed after rolling . . .	6	20–23	65–75	60

The effect of cold-rolling upon the mechanical properties of 70/30
cartridge brass strip is illustrated in Fig. 77.† The results show how
the tensile strength, proof stress and hardness increase progressively
with the amount of cold-rolling whilst the ductility diminishes con-
tinuously.

Temper of Brasses. The effect of the amount of cold work is usually
referred to as the "*temper*" of the metal. The *soft* temper condition
refers to the annealed metal with a Brinell hardness below about 80.
The *quarter* and *half-hard* tempers cover metal of about 80 to 120
Brinell hardness. *Hard temper* metal has a Brinell hardness of about

* See Table 46.
† C.D.A. publication, "Brasses."

120 to 150, whilst *spring hard temper* refers to hardnesses of 150 Brinell upwards.

In regard to the *fatigue or endurance limit* of wrought brasses of
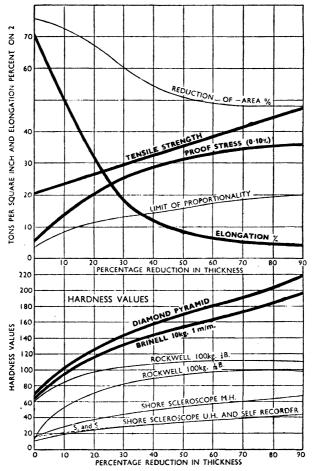
FIG. 77. EFFECT OF COLD-ROLLING ON THE MECHANICAL PROPERTIES OF 70/30 BRASS STRIP

85 per cent copper and downwards, this usually lies between $\pm$ 6 and $\pm$ 10 tons per sq. in. for 50 million stress reversals. Cold-worked alpha brasses, if subjected to low temperature heat-treatments at 250° to 270° C., can give endurance values up to $\pm$ 13 tons per sq. in. for 50 million stress reversals.

Corrosion Resistance. In regard to the corrosion resistance of brasses, those of higher copper content have greater resistance to many forms of corrosion than those of lower copper content containing the beta constituent.

In general the brasses offer very good resistance to atmospheric corrosion, being greatly superior to ordinary steels and iron. For improved corrosion resistance properties small proportions of other constituents such as aluminium and tin may be made. Thus for condenser tubes a small amount of aluminium is employed and for marine purposes, tin.

Admiralty or Naval Brass. A typical corrosion resisting brass known as Admiralty Naval Brass has about 1 per cent of tin. It conforms to the British Standard Specification No. 251, and has the following percentage composition: Cu, 61·0 (min.); Sn, 1·0; Total impurities, 0·75 (max.); Zn, the remainder.

Aluminium Brass. As previously noted, aluminium is included in certain brasses for the purpose of improving their resistance to corrosion. With about 2 per cent of aluminium the resulting 76/22 brass has good sea-water corrosion resistance and is used for marine condenser tubes and other exposed parts. It has a tensile strength (extruded) of 22 tons per sq. in. with 70 per cent elongation and 6 tons per sq. in. proof stress. In the hard-drawn condition the tensile strength is increased to 40 tons per sq. in. with about 10 per cent elongation and 28 tons per sq. in. proof stress.

Improved Machinable Brass

In order to improve the machining properties of certain brasses small amounts of lead are added. Thus in the case of 60/40 brass additions of 1 to 3 per cent of lead render it "free-cutting." The lead does not alloy itself with the copper or zinc but separates into very small isolated globules which, during machining operations, cause the turnings to break off short so as to free themselves readily from the cutting edge of the tool.

A typical brass of this kind is that conforming to the British Standard Specification No. 249 (Brass Bars for High Speed Screwing and Turning) which has the following percentage composition: Cu, 56 to 60; Pb, 1·75 to 3·0; Total impurities, 0·75 (max.); Zn, the remainder.

This metal has a minimum tensile strength of 20 tons per sq. in. with a minimum elongation of 20 per cent.

The *cutting speeds* for lead-containing brasses of this class can be much higher than for ordinary brasses or free-cutting steel so that a marked saving in manufacturing costs can be effected.

High Tensile Strength Brasses

This group of brasses consists of copper-zinc alloys of the 60/40 type with the addition of small percentages of other elements such as manganese, aluminium, iron, tin or nickel, to improve the tensile strength values. The percentages of the added element or elements generally lie between about 0·5 and 3·0. The added element is usually present in the form of solid solution, often dissolving in the *beta* phase. Some of the elements appear to act in a similar manner to zinc, but in a different proportion, in the copper-zinc alloy.

In this connection it may be of interest to mention a principle originally put forward by Guillet in 1906, which expresses the zinc replacement capacity of various elements when added to brass. These equivalents are given in Table 48. Thus, the effect of 1 per cent of silicon in brass is approximately the same as 10 per cent of zinc; 1 per cent of aluminium as 6 per cent of zinc; and so on.

TABLE 48

EQUIVALENT VALUES OF ELEMENTS TO ZINC IN COPPER-ZINC ALLOYS

Element	Equivalent Value	Element	Equivalent Value
Nickel . . .	-- 1·2	Magnesium . .	2
Manganese . .	0·5	Tin . . .	2
Iron . . .	0·9	Aluminium . .	6
Lead . . .	1·0	Silicon . . .	10

In regard to the negative value for nickel in Table 48, this indicates that 1 per cent of nickel operates in a similar manner to 1·2 per cent of copper. It is of interest to note that although this principle was discovered so long ago it applies, with certain reservations (in the case of complex alloys), to the microstructures.

Aluminium High Tensile Strength Brasses

These high strength brasses have been referred to previously, in regard to their good corrosion resistance properties. As cast the tensile strengths are high, but with small elongations.

The aluminium content does not exceed 4 per cent and since the equivalent value of aluminium is high the copper content must also be kept up; thus, the best results are obtained with about 60 per cent of copper.

The effect of increasing proportions of aluminium on chill cast brasses of the 60/40 composition is shown in Table 49.*

TABLE 49

EFFECT OF ALUMINIUM ON CHILL CAST BRASSES

Composition			Yield Point Tons per sq. in.	Max. Stress Tons per sq. in.	Elonga- tion per cent on 2 in.	Reduc- tion of Area per cent	Brinell Hard- ness
Copper per cent	Zinc per cent	Alumi- nium per cent					
58·96	41·04	Nil	8·8	24·9	45·0	49·7	90
59·48	39·52	1·00	14·8	32·0	30·0	33·5	114
58·35	40·11	1·54	16·4	35·2	17·0	18·5	129
58·26	39·56	2·18	16·0	36·4	16·0	21·5	138
59·85	37·13	3·02	22·3	42·0	18·5	21·5	159

From these results it will be observed that the tensile strength and hardness increase with the aluminium content up to the maximum amount tested, namely, 3·02 per cent. The elongation diminishes quickly at first but remains fairly steady for 2 to 3 per cent aluminium content.

Some further results for high tensile aluminium brasses of higher aluminium content are given in Table 50.†

TABLE 50

MECHANICAL PROPERTIES OF TYPICAL HIGH TENSILE ALUMINIUM BRASSES

Condi- tion	Copper per cent	Zinc per cent	Alumi- nium per cent	Iron per cent	Nickel per cent	Yield Point Tons per sq. in.	Tensile Strength Tons per sq. in.	Elonga- tion per cent	Brinell Hardness 10 kg. per 1 mm.
Cast Forged }	58·85	38·05	3·10	—	— {	20·5 18·9	38·6 43·0	19 29	148 159
Cast .	60·0	31·45	4·10	1·45	3·0	—	44·5	12	—

The aluminium brasses have a bright yellow colour and are all strongly resistant to corrosion, but cannot readily be soldered. A still

* *Amer. Inst. Min. Met. Eng.*, O. Smalley, 1926, 73, 799.
† "Copper and Its Alloys," F. A. Fox, *Machinery*, 19th May, 1938.

further improvement in the corrosion resisting qualities is effected by the addition of about 2 to 3 per cent of nickel; certain types of marine propellers are made of such alloys.

Manganese Bronze

This term is a misnomer as it is the name given to a 60/40 brass containing small additions of manganese, and tin or aluminium for hardening and strengthening purposes. The manganese content is about 1 per cent, although low manganese high tensile brasses containing up to 0·05 per cent manganese have higher mechanical properties than those without this element. When both aluminium and manganese are present in equal but small proportions, tensile strengths of 30 tons per sq. in. are obtained in the cast condition.

A typical manganese bronze used for castings to replace certain steel and malleable iron forgings, water pump rotors and marine propellers has the following percentage composition: Cu, 56·0; Zn, 41·5; Mn, 0·25; Fe, 1·0; Sn, 1·0; Al, 0·25.

In the sand-cast state this alloy has a yield point and tensile strength of 17 and 34 tons per sq. in. respectively, with 28 per cent elongation. The limit of proportionality is 11 tons per sq. in. and Brinell hardness 140. A typical manganese bronze of the extrusion and hot-rolled kind has a tensile strength of about 35 tons per sq. in. with 22 per cent elongation and 0·15 per cent proof stress of 17 tons per sq. in.

The manganese bronzes can be readily extruded and hot stamped. They are employed in automobile work for gear-box selector forks, various bushes, control gear pinions, high tensile cylinder and exhaust joint nuts, pump casings, etc. These alloys have also been used for locomotive and truck axle-boxes.

Standard High Tensile Strength Brasses

A number of high strength brasses for castings and in the bar and section form are included in the British Standard Specifications.

The B.S.S. No. 208 refers to high tensile brass castings and includes five classes specified to give minimum tensile strengths of 28 to 45 tons per sq. in. with corresponding proof stresses of 12 to 25 tons per sq. in. and minimum elongations of 25 down to 12 per cent. Higher values are possible from certain commercial high tensile brasses when in the hot-worked condition, and cold-working will increase the tensile strengths still further, but with a loss of ductility.

In regard to the *impact resistance* of these brasses Izod impact values of 20 to 30 ft./lb. are obtained from the extruded forms.

The B.S.S. No. 250 relates to high tensile brass bars and sections

containing 54 to 62 per cent copper and the remainder (with the exception of alloying elements up to 5 per cent) zinc. Two grades are specified, namely, (1) Grade A, with a minimum tensile strength of 30 tons per sq. in.; 0·15 per cent proof stress of 15 tons per sq. in., and 25 per cent (minimum) elongation; and (2) Grade B, with corresponding values of 35 and 18 tons per sq. in. and 20 per cent respectively.

Temper-hardening Brasses

A more recent group of brasses now available commercially possesses the property of being strengthened by suitable heat-treatment processes in a somewhat similar manner to duralumin. This hardening property is due to the combined presence of nickel and aluminium or other elements in given proportions.

A typical temper-hardening brass has the following percentage composition: Cu, 72; Ni, 6·0; Al, 1·5; Zn, 20·5. In the soft condition, which is obtained by quenching from 850° C., the metal has a tensile strength of 23 tons per sq. in., proof stress of 5 tons per sq. in., and elongation of 60 per cent.

When heat-treated at 500° C. the corresponding values are 36, 22 and 30 respectively. If, however, the alloy is heat-treated after cold work the values of the tensile strength and proof stress are increased to 48 and 45 per cent respectively, and the elongation reduced to 11 per cent.

Strength of Copper Alloys at Elevated Temperatures

The alpha brasses with their higher copper content possess better strength properties at elevated temperatures than the alpha-beta and beta brasses, and they have also better creep characteristics at higher temperatures. Some experimental results* are given in Table 51 for two types of brass, namely, the 60/40 and 70/30 and it will be observed from these values that the higher copper content brass is much stronger and more ductile at 427° C. than the lower content one.

In regard to the creep resistance of the alpha and alpha-beta brasses, the inferiority of the alpha-beta alloys at high temperatures is illustrated by the values given in Table 52 due to C. L. Clark and A. E. White.

The strengths at elevated temperatures of other alloys of copper, including special brasses, bronzes and other alloys, vary considerably according to their compositions and condition, i.e. whether cast, wrought, annealed, etc. In general the strongest bronzes at elevated

* C. L. Clark and A. E. White, *Amer. Soc. Mech. Eng.*, 1930 and 1932.

TABLE 51

STRENGTHS OF BRASSES AT ELEVATED TEMPERATURES

	Temperature			
	75° F.	400° F.	600° F.	800° F.
Material and Properties	24° C.	205° C.	315° C.	427° C.
70 : 30 _Brass_ (cold drawn—26 per cent reduction)—				
Limit of proportionality, tons per sq. in.	10·3	5·8	3·0	1·8
Tensile strength, tons per sq. in. .	31·3	29·3	23·0	9·4
Elongation, per cent on 2 in. . .	24·3	12·0	4·5	26·0
Reduction of area, per cent . .	61·5	28·5	9·0	23·0
60 : 40 _Brass_ (hot rolled)—				
Limit of proportionality, tons per sq. in.	4·9	2·5	0·67	0·22
Tensile strength, tons per sq. in. .	24·7	21·2	11·4	3·9
Elongation, per cent on 2 in. .	51·0	50·5	40·0	18·0
Reduction of area, per cent . .	57·2	57·9	37·5	25·6

TABLE 52

CREEP CHARACTERISTICS OF COMMERCIAL BRASSES AT ELEVATED TEMPERATURES

Material	Temperature		Stress (Tons per sq. in.) to Produce Designated Rate of Creep			
	Deg. Fahr.	Deg. Cent.	No Measurable Flow	Rate of Creep, 0·01 per cent Flow per 1000 Hours	Rate of Creep, 0·10 per cent Flow per 1000 Hours	Rate of Creep, 1·00 per cent Flow per 1000 Hours
85 Cu 15 Zn .	400	205	3·3	3·9	5·4	7·6
	600	315	(a)	0·45	1·2	3·0
77 Cu 22 Zn 1 Sn	400	205	3·3	4·7	5·8	7·4
	600	315	(a)	0·54	1·1	2·4
70 Cu 30 Zn .	400	205	4·5	5·7	8·0	12·0
	600	315	(a)	0·13	0·38	0·96
70 Cu 29 Zn 1 Sn	400	205	4·5	5·8	8·5	12·0
	600	315	(a)	0·45	0·87	1·7
60 Cu 40 Zn .	300	150	3·3	4·0	5·4	7·6
	400	205	(a)	0·9	2·1	5·1
59 Cu 40 Zn 1 Sn	300	150	4·5	5·4	6·7	9·6
	400	205	(a)	1·6	2·5	4·2

(a) Known to be very small and believed to approach zero.

TABLE 53

PROPERTIES OF COPPER ALLOYS AT ELEVATED TEMPERATURES

Material	Condition (all Materials Wrought unless stated otherwise)	Tensile Strength (Tons per sq. in.)				Elongation per cent on 2 in.			
		Ord. Temp.	300° C.	400° C.	500° C.	Ord. Temp.	300° C.	400° C.	500° C.
Copper	Annealed	14	10	6	4	60	50	30	20
Temper Hardened Copper Alloys									
98·75 Cu, 0·75 Ni, 0·5 Si	Temper hardened	24	21	18	15	35	30	36	3
99·5 Cu, 0·5 Cr	Cast and heat-treated	23	—	18	—	25	—	20	—
97 Cu, 2·6 Co, 0·4 Be	Cast and heat-treated	40	30 (250°)	—	25 (475°)	10	4 (340°)	—	1 (475°)
92·5 Cu, 6 Ni, 1·5 Al	Temper hardened	44	24	20	16	20	11	5	4
Brasses									
90 Cu, 10 Zn	Annealed	17	11	8	6	56	30	10	15
60 Cu, 40 Zn	Annealed	25	12	6	1	52	42	22	—
57 Cu, 40 Zn, 1·7 Fe, 0·4 Al, 0·5 Pb	Cast	27	14	7	—	15	70	100	—
Bronzes									
88 Cu, 10 Sn, 2 Zn	Cast	16	10	7	—	20	8	2	—
92 Cu, 11 Sn, 7 Ni	Cast	20	16	—	—	20	16	—	—
90 Cu, 10 Sn	Annealed	29	16	—	—	63	10	—	—
"Chromium bronze"	Annealed	25	23	18	11	38	40	38	40
Aluminium Bronzes									
90 Cu, 10 Al	—	38	33	24	12	29	32	41	66
80 Cu, 10 Al, 5 Ni, 5 Fe	—	53	—	24 (425°)	—	16	—	37 (425°)	—
Other Alloys									
96 Cu, 3 Si, 1 Mn	Annealed	33	24	16	9	43	30	25	20
75 Cu, 25 Ni	Annealed	24	18	16	13	37	33	30	20
68 Ni, 32 Cu	Annealed	37	34	30	23	45	42	35	22
50 Ni, 10 Sn, 40 Cu		38	—	32	26	1	—	1	1
95 Cu, 5 Mn	Cast	22	21	16	—	37	37	24	—

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temperatures are the nickel, chromium, and aluminium bronzes : these are considerably stronger than the brasses. The other copper alloys most suitable for elevated temperature service appear to be those containing small proportions of tin, nickel, aluminium and manganese.

The *copper-nickel-silicon* alloys having 0·75 to 2·0 per cent silicon and 0·5 per cent silicon—of which *Kuprodur* is a well-known example that is used for locomotive fire-boxes—are also suitable for use at elevated temperatures. These alloys possess precipitation hardening properties, but are inclined to be brittle with higher nickel content than 1 per cent. In regard to the bronzes, whilst the plain copper-tin ones give good service for such purpose as boiler mountings, the nickel bronzes are stronger, whilst the chromium bronzes are superior in strength properties at elevated temperatures.

For special applications where maximum strength and corrosion resistance are required the *high nickel-copper* and *nickel-copper-tin* alloys possess about the greatest strengths for temperatures of 300° C. to 500° C. Table 53* gives particulars of a number of copper-base alloys and their tensile strengths and elongations over the 300° C. to 500° C. temperature range.

Some further information on the subject of high temperature properties of copper alloys is given in the graphs shown in Fig. 95, on page 200.

The Bronzes

The term "bronze" is normally applied to the alloys of copper and tin, but more generally, with the addition of other elements such as zinc, nickel, phosphorus, aluminium, lead, etc., other alloys are now included. Typical instances of these are phosphor bronze, gunmetal, lead-bronze, plastic-bronze, nickel-bronze.

The copper-tin alloys usually contain from 5 to 20 per cent of tin, although most of the useful commercial bearing alloys contain from 10 to 12 per cent of tin ; other cast gunmetals have from 5 to 10 per cent of tin.

The approximate equilibrium diagram for the copper-rich alloys of copper and tin is shown in Fig. 78,† from which it will be seen that the alpha solid solution range is from 0 to 16 per cent tin content. For greater tin contents there is a eutectoid transformation with an *alpha-delta* eutectoid. The equilibrium conditions appear difficult to establish in the bronzes due to occurrence of unstable phases and

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* "Copper Alloys in Engineering," H. J. Miller, *The Metal Industry*, 11th 8th, and 25th November, 1938.

† "Copper and Its Alloys," F. A. Fox, *Machinery*, 19th May. 1938.

reluctance in diffusion. One result of these difficulties is a variation in the mechanical properties as affected by casting conditions. The
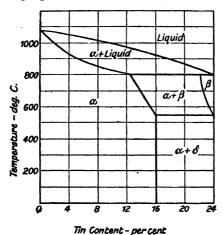
FIG. 78. EQUILIBRIUM DIAGRAM FOR COPPER-RICH COPPER-TIN ALLOYS

FIG. 79. STRUCTURE OF COPPER-TIN BEARING BRONZE, SHOWING
DUPLEX STRUCTURE
The softer alpha areas appear white and the harder delta areas dark.
(*C.D.A.*)

alloys containing up to about 7 per čent of tin resemble in their properties the alpha brasses, but are harder; they possess good cold-working properties and corrosion resistance.

In regard to the structure of copper-rich alloys of copper and tin, although variations in the melting and casting conditions cause modifications, in general these alloys reveal a duplex structure similar to

that shown in Fig. 79. This consists of a hard tin-copper constituent, namely, the *delta*, in a softer *alpha* matrix. When the percentage of tin is increased above 7 per cent the amount of the harder constituent increases progressively and the strength and hardness also increase. Above about 12 per cent tin content the delta content produces great hardness, but with increased brittleness, so that a limit of usefulness for most commercial purposes is reached at about 15 per cent tin content, although for special applications as much as 20 per cent of tin is employed.

Thus the 15 per cent tin bronze is used for locomotive slide valves, as it possesses great hardness and wear resistance.

With the addition of small amounts of iron, chromium or vanadium, however, the tin content can be raised, whilst with 0·25 to 5·0 per cent of manganese, tin amounts up to 20 per cent can be employed in making hot-working bronzes.

The bronzes containing up to about 10 per cent tin can be produced in the form of cold-drawn rod or tube. As work-hardened in this manner, after annealing, the bronzes have a homogeneous structure consisting only of the alpha constituent. Such bronzes are suitable for medium-duty bearings and bushes.

In general the copper-tin bronzes have poor hot-working properties and it is usual to limit the tin content to about 3 per cent for hot-working.

Effects of Other Elements in Copper-tin Bronzes

It is now customary to add small percentages of other elements to copper-tin bronzes in order to improve their properties. The principal elements employed for this purpose are phosphorus, lead, zinc and nickel; the effects of these elements are briefly as follows—

Phosphorus. This acts as a deoxidizer and improves the casting qualities. When present up to 0·1 per cent the hard tin-oxide which is liable to occur in plain copper-tin bronze and is the cause of hardness and scoring in service is removed; the crystal structure and wearing properties are thereby improved. From 0·1 to 0·5 per cent of phosphorus above that needed for deoxidization introduces a very hard copper-phosphide compound which increases the hardness but tends to make it more brittle.

Lead. Lead does not enter into the copper and remains as a separate constituent in the form of microscopic globules distributed through the bronze and *improves its plasticity*, so that these bronzes can compensate to some extent for small inaccuracies of alignment in bearings. A further advantage is that such leaded bronzes can be used for

bearings of unhardened steel shafting and in the event of temporary failure of oil supply are not so liable to seize as ordinary bronze bearings. From 1 to 2 per cent of lead *improves the machinability.* Lead in amounts of 5 per cent and upwards reduces the dry coefficient of friction; up to 12 per cent it improves the plasticity but reduces the toughness. Reference to the leaded bronzes with more than 20 per cent lead is made later.

Zinc. This metal acts as a deoxidizer, and is often used instead of phosphorus for the purpose. The copper-tin bronzes containing up to 6 per cent of zinc are known as *gunmetals.*

Nickel. The effect of addition of nickel up to 2 to 3 per cent on copper-tin bronzes is to give an increase in tensile strength and toughness and to refine the crystal structure. In the case of leaded bronzes it has been claimed that the distribution of the lead particles is improved. The results of a comprehensive series of tests by N. B. Pilling and T. E. Kihlgren* upon various bronzes showed that in the case of a gear bronze containing approximately 87 per cent Cu, 11 per cent Sn, and 2 per cent Ni, the limit of proportionality in tension and compression was increased by 25 per cent as compared with the nickel-free base alloy. The yield point was also increased by 15 per cent. No loss of ductility occurred with nickel up to 3 per cent.

In the case of a high lead bronze of the following percentage composition, namely, Cu, 70; Sn, 7; Zn, 1·0; Pb, 21; Ni, 1·0, the limit of proportionality was increased by 50 per cent and the yield point by 20 per cent by the 1·0 per cent nickel addition to the basic alloy.

The addition of nickel gives a slight increase in the melting point, namely, of 6·6° C. per 1 per cent nickel when it replaces copper and 18° C. when the nickel replaces tin. It is also claimed to densify the metal and minimize the tendency towards incipient shrinkage cracks in certain bronzes. Further information on this subject will be found under the heading of "Nickel Bronzes."

Gunmetals

These are alloys of copper, tin and zinc, with the latter element in small proportions up to 6 per cent (maximum). Usually, however, the percentage of zinc is limited to 2·5 owing to the tendency towards brittleness with greater proportions.

The zinc, as stated previously, improves the casting properties and enables sounder castings to be produced. It is also a much cheaper metal than tin so that its use enables an economy to be effected. A typical composition is that of Admiralty gunmetal having the following

* *Nickel Bronzes,* Bureau of Information on Nickel.

percentages of elements: Cu, 88; Sn, 10; Zn, 2. The average mechanical properties for the sand cast metal are as follows: Tensile strength, 17 tons per sq. in.; elongation, 20·0 per cent on 2 in.; Brinell hardness, 65.

In general rather better strength properties are obtained from sand cast than from chill cast gunmetal and although annealing is not usually recommended it improves the properties in some cases. In this connection the results of some tests* are given in Table 54.

TABLE 54

MECHANICAL PROPERTIES OF GUNMETAL

Condition	Yield Point Tons per sq. in.	Tensile Strength Tons per sq. in.	Elongation per cent
Dry sand cast, slow solidification, slow cooling	11·0	17·2	24·0
Dry sand cast, subsequently annealed for ½ hour at 700° C.	10·5	18·0	37·5
Chill cast, rapid solidification, rapid cooling	8·5	15·0	4·0
Chill cast, subsequently annealed for ½ hour at 700° C.	11·5	20·0	30·0

Gunmetals are used for less expensive sand castings than the alloy bronzes where harder and better wearing qualities are required than for brass parts. Typical applications include gear-wheels, pump casings, bearings, bushings, and marine fittings.

Phosphor Bronze

The phosphor bronzes are copper-tin alloys having 0·1 to 1·5 per cent of phosphorus, the latter element being included not only for the purpose of deoxidizing but also to improve the structure and general strength properties of the metal.

The copper-tin alloys employed contain from 5 to 20 per cent of tin, 0·1 to 1·5 per cent of phosphorus and the rest copper. The phosphorus, as stated previously, results in the formation of the very hard copper-phosphide constituent (Cu_3P); this improves the hardness and wear resistance.

The cold-workable phosphor bronzes contain from 0·1 to 0·4 per cent of phosphorus and a maximum of about 7 per cent of tin. Such

* *Ante*, page 163, note (lower reference).

bronzes can be rolled and extruded and give high tensile strengths and a high elastic limit. For this reason they are suitable for making springs for applications where high corrosion resistance is required. In the rolled strip form these bronzes will give tensile strengths up to 40 tons per sq. in.

Phosphor Bronze Wire. When employed for wire drawing purposes the tensile strength increases in proportion to the percentage reduction
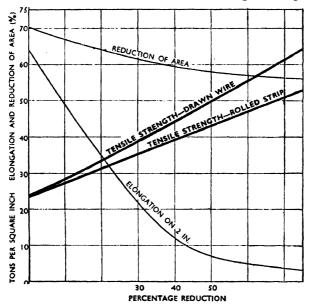
FIG. 80. EFFECT OF COLD WORKING ON MECHANICAL PROPERTIES OF PHOSPHOR BRONZE (6% TIN)

of section, whilst the elongation decreases considerably. Some results of tests made upon phosphor bronze of 6 per cent tin content, which was subjected to progressive cold working by rolling and drawing through dies, are given in Fig. 80. It will be observed that the tensile strength and elongation for the original metal were 24 tons per sq. in. and 63 per cent respectively. When rolled as strip with 75 per cent reduction the tensile strength was increased to 53 tons per sq. in. with about 3 per cent elongation; when drawn as wire with the same percentage reduction the tensile strength was increased to 64 tons per sq. in. with about 3 per cent elongation.

There are two grades* of phosphor bronze used for wire making,

* British Standard Specification No. 384.

namely, the *Low Tin Bronze* (Grade A) containing from 3·5 to 5·0 per cent tin and the *High Tin Bronze* (Grade B) having from 4·5 to 7·0 per cent tin.

The minimum mechanical properties of wires made from these bronzes are given in Table 55, based upon B.S.S. No. 384.

TABLE 55

MECHANICAL PROPERTIES OF PHOSPHOR BRONZE WIRES

Nominal Diameter of Wire (inch)	Grade	Minimum Proportion-ality Limit Tons per sq. in.	Minimum Tensile Strength Tons per sq. in.	Minimum Elongation per cent on 8 in.
0·032 up to 0·064 . .	Low tin	20	56	0·50
	High tin	22	62	0·50
Above 0·064 up to 0·104	Low tin	20	56	0·75
	High tin	22	62	0·75
Above 0·104 up to 0·160	Low tin	17	54	0·75
	High tin	22	62	0·75

The *modulus of elasticity* value is about 18×10^6 lb. per sq. in. and the *modulus of rigidity* $6·5 \times 10^6$ lb. per sq. in.

In connection with the use of phosphor bronze wire for springs the *torsional stress* value above which permanent set may occur is 45,000 lb. per sq. in. Using these values in the case of helical coil springs (close-coiled) in the following general formulae, viz.—

$$f = \frac{8PD^3n}{Cd^4}$$

$$S = \frac{8PD}{\pi d^3}$$

where f = total deflection (inches); n = number of coils; P = applied load (lb.); D = mean diameter of coils (inches); C = modulus of rigidity; d = diameter of wire (inches), and S = torsional stress (lb. per sq. in.), we obtain—

$$f = \frac{0·02176D^2}{d}$$

and Safe Load (lb.) $= \frac{17680d^3}{D} \times \frac{1}{K}$ where K = factor of safety.

Higher Tin Content Phosphor Bronzes. When the tin content is increased to 9 to 13 per cent, with 0·5 to 1·5 per cent phosphorus, the

alloys, on account of the greater percentage of copper phosphide, are very hard and possess excellent wear resistance. Moreover, they have also a low coefficient of friction and are therefore very suitable for use as *bearings* and for *gear wheels*. Bronzes with a lower tin and phosphorus content are used for steam and hydraulic valves and seatings. The phosphor bronzes, on account of their *non-sparking properties* when struck with other metals, are useful for tools that have to be used in the vicinity of explosive gases, vapours, etc.
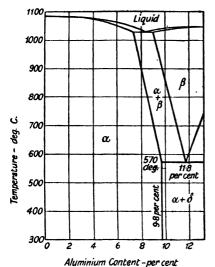
FIG. 81. EQUILIBRIUM DIAGRAM OF COPPER-ALUMINIUM ALLOYS

Phosphor bronzes with 9 to 12 per cent tin and 0·4 to 0·5 per cent phosphorus are suitable for castings of gudgeon pin and similar bushes, bearings, valve guides, worm wheels (for automobile final drives and general engineering purposes). Phosphor bronzes of 5 to 7 per cent tin content possess very good resistance to sea-water corrosion and are used for marine fittings; they have also given good results for steam turbine blading.

Aluminium Bronze

The beneficial effects of aluminium in the case of high tensile brasses containing up to 4 per cent aluminium have already been noted; its influence upon the mechanical and physical properties of copper, with the addition of appreciable quantities of other elements, e.g. iron, nickel, and manganese, but in higher percentages, up to about 14, will now be considered.

Actually, these so-called "bronzes" contain no tin, the principal alloying elements being copper and aluminium.

The equilibrium diagram for copper-aluminium alloys of the copper-rich range is given in Fig. 81. It shows an *alpha* solution up to 9·8 per cent aluminium, beyond which a *beta* phase of an unstable nature occurs in the hot alloy; this breaks down at 570° C. into a mixture of *alpha* phase and a *delta* phase. The *alpha-delta* eutectoid whilst being hard also tends to be brittle; for this reason it is usual in commercial alloys to limit the aluminium content to a maximum of 10 to 11 per cent.

Commercial aluminium bronzes can be arranged into two groups, namely (1) those containing 4 to 7 per cent aluminium of the *alpha* phase homogeneous structure class, and (2) those containing about 8 up to 14 per cent aluminium, having a duplex structure; these bronzes include also additions of iron, manganese, nickel, and other elements in considerable amounts.

Alloys of the former group possess good ductility and can be worked both hot and cold and are thus obtainable in the form of sheet, strip, tubes and wire for a wide range of applications. They are not, however, noted for high strength properties, being little superior to the *alpha* brasses, but their corrosion resistance is much better, so that they are more suitable for components exposed to severe corrosion conditions.

Alloys of the second group in which the *beta* constituent is present in appreciable quantities are much harder but less ductile at ordinary temperatures, so that they can be cold-worked only to limited extents depending on the amount of *beta phase*. On the other hand, since the *beta* constituent is relatively soft at high temperatures these alloys are more easily hot-worked by forging, stamping, rolling and extruding. The 8·5 to 11 per cent aluminium bronzes are therefore of considerable commercial importance in hot-worked shapes.

Physical Properties of Aluminium Bronzes

The specific gravity varies with the aluminium content from 8·8 for 1 per cent of the latter, down to 7·44 for 11 per cent.

The thermal expansion per ° C. of bronze of 10 per cent aluminium content is 0·000017 over a temperature range of 20° C. to 100° C. and 0·000018 over a range of 20° C. to 250° C.

The thermal conductivity in C.G.S. units, from 20° C. to 200° C., is 0·18. The electrical conductivity is usually taken as being about 12 per cent of that of high conductivity copper, but the conductivity is decreased by additions of iron and nickel.

The commercial aluminium bronzes are practically non-magnetic, but certain complex bronzes containing appreciable proportions of iron are slightly magnetic.

Mechanical Properties

In regard to the mechanical properties of the copper-aluminium alloys, the general manner in which the tensile strength and elongation of the alloys in question vary with aluminium content, based upon the results of Carpenter and Edwards,* is shown for both cast and hot-rolled alloys in Fig. 82.†

* *Proc. Inst. Mech. Engrs.*, 1907, 57.
† *Aluminium Bronze*, C.D.A. Publication, 1939.

The tensile strength and ductility both increase with the aluminium content up to about 7 to 7·5 per cent. The maximum ductility occurs for the cast metal over a range of 5 to 7 per cent aluminium, with the high value of about 70 per cent elongation. The hot-rolled metal has
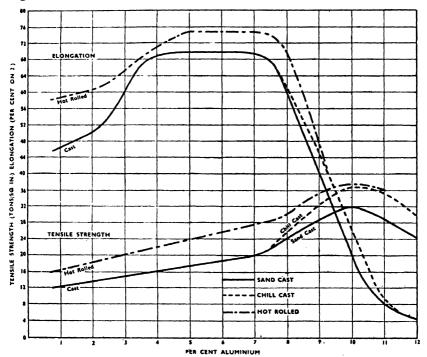
FIG. 82. GENERAL MECHANICAL PROPERTIES OF CAST AND WROUGHT
COPPER-ALUMINIUM ALLOYS
(C.D.A.)

a higher elongation, namely, 75 per cent over the wider range of 4 to 7 per cent aluminium.

The maximum tensile strengths for the hot-rolled and sand cast alloys occur at 10 per cent aluminium, the values being about 38 and 32 tons per sq. in. respectively; the corresponding elongations are 26 and 20 per cent respectively.

The effect of chill casting in increasing the maximum tensile strength is shown by the tensile strength curve, which approaches closely to that for the hot-rolled specimen.

The *modulus of elasticity* for the range of commercial aluminium bronzes is 17·5 to 19·0 × 10⁶ lb. per sq. in.

The *Izod impact strength* in the alpha range bronzes is from 50 to 65 ft.-lb. This range of strength values applies to both the annealed and work-hardened conditions.

Strength at Elevated Temperatures

The aluminium bronzes have good strength properties at temperatures up to 450° to 550° C. The results of tests made by Rosenhain and Lantsbury* are summarized in Table 56, and these show that in the case of the 90·06 Cu, 9·9 Al bronze a tensile strength of 9·1 tons per sq. in. with 10 per cent elongation was obtained at 550° C.

In regard to *creep properties* these are considered to be about the best of any of the well-known copper alloys, especially those used for castings; they are not so good, however, as certain complex alloys, such as the 80 Cu, 5 Al, 5 Ni, 5 Fe alloy.

TABLE 56

PROPERTIES OF ALUMINIUM BRONZES AT ELEVATED
TEMPERATURES

Temperature of Test (°C.)	Alloy Composition					
	93·23 Cu, 6·73 Al		90·06 Cu, 9·9 Al		89·1 Cu, 9·9 Al 1·0 Mn	
	Tensile Strength Tons per sq. in.	Elongation on 2 in.	Tensile Strength Tons per sq. in.	Elongation on 2 in.	Tensile Strength Tons per sq. in.	Elongation on 2 in.
15	28·8	7⅟	38·1	29	41·7	30
200	—	—	36·4	36	39·6	36
300	20·7	25	33·4	32	36·4	47
400	17·9	16	24·0	41	22·7	57
450	13·3	10	22·3	31	17·3	51
500	10·9	14	12·1	66	—	—
550	—	—	9·1	10	—	—

The *alpha bronzes*, which are used almost entirely for fabricated forms, contain up to about 7·5 per cent of aluminium, sometimes with the addition of nickel up to 4 per cent, and these can be cold-worked to a considerable extent; their mechanical properties are improved to a marked degree by cold-working. In regard to the effect of cold-working upon the tensile strength and elongation of 5 per cent aluminium bronze strip the tensile strength is increased from about

* *Proc. Inst. Mech. Engrs.*, 1910, 119.

25·5 to 54·5 tons per sq. in. for an 80 per cent reduction in thickness by cold rolling, whilst over the same range of cold-working the hardness is increased from about 70 to 205 Brinell. The accompanying loss of ductility is indicated by the drop in elongation from about 71 to 4 per cent.

The *alpha aluminium bronzes are annealed* at somewhat higher temperatures than for alpha brasses and tin bronzes. It is necessary
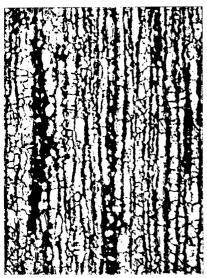
FIG. 83. EFFECT OF COLD ROLLING ON THE GRAIN SIZE OF 91 CU, 9 AL BRONZE. LONGITUDINAL SECTION. × 100
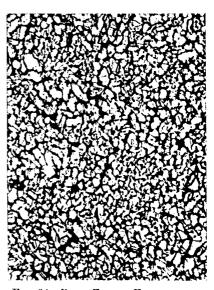
FIG. 84. REAR END AS EXTRUDED OF 91 CU, 9 AL BRONZE. TRANSVERSE SECTION. × 100

to heat them to at least 650° C. for complete softening; quenching in place of slow cooling appears to have no effect on the mechanical properties except in the case of alloys with more than 7·5 per cent aluminium, where there is an increase in hardness due to the retention of some of the *beta phase*. The grain size may be controlled by annealing, whilst the effect of cold rolling or drawing results in the deformation of the annealed structure causing an elongation of the individual crystals in the direction of working. These results are illustrated in the photomicrographs reproduced* in Figs. 83 and 84, for the 91 Cu, 9 Al alloy in the extruded longitudinal and extruded transverse sections respectively.

* I.C.I. (Metals) test results.

The hot-working aluminium bronzes have aluminium contents of 8·5 to 11 per cent and are all of the duplex type of structure. These bronzes usually contain, in addition, iron, nickel, manganese and lead, according to the purpose for which they are required.

The compositions and tensile strength properties of some typical hot-working aluminium bronzes are given in Table No. 57.*

TABLE 57

TYPICAL ALUMINIUM BRONZES FOR HOT-WORKING PURPOSES

Composition, per cent						Specifications and General Comments
Copper	Alu-minium	Iron	Nickel	Man-ganese	Lead	
90–91	9–9·8	—	—	—	—	Conforms to D.T.D. 160. Usually possesses a tensile strength of 35 tons/sq. in.
89	9·7–90·5	—	1·0–1·5	...	—	Conforms to D.T.D. 135. Tensile strength exceeds 40 tons/sq. in.
86	9–10	0·5–2·5	1·0–3·0	...	...	Conforms to D.T.D. 164. Usually possesses a tensile strength exceeding 40 tons/sq. in. (38 tons/sq. in. minimum).
80	8–12	4–6	4–6	—	—	Conforms to D.T.D. 197. Tensile strength usually exceeds 50 tons/sq. in. (45 tons/sq. in. minimum).
88	9	2–3	—	...	...	Alloys widely used for extruded and forged rods, bars, etc. Tensile strength is 32 tons/sq. in. upwards, depending largely on aluminium content and structural condition. Generally only those alloys with an average aluminium content of 10 per cent are accorded heat-treatment operations.
88	9–10	1·5	—	0·5	...	
85	9–10	2–4	—	2	—	
90	9·5–10·5	—	—	...	...	
88	9·5–10·5	—	2	—	...	
83	10–11	5	1	1	—	
87	9–10	—	1·5	—	1·5	For free cutting purposes.

* Copper Development Association.

The effect of cold-working in the case of the 10 per cent aluminium alloy is illustrated by the results of tests made on cold-drawn rod having an initial tensile strength of 35 tons per sq. in., with 30 per cent reduction of area, 19 per cent elongation, and a Brinell hardness of about 130. When reduced by cold drawing by 20 per cent in area the corresponding values were 49 tons per sq. in.; 10 per cent; 5·5 per cent and 186 respectively.

The constitution and structure of the alloys having more than 7·5 per cent of aluminium are capable of *modification by heat-treatment* —as shown by the equilibrium diagram given in Fig. 81. Quenching from a high temperature results in the retention of an excess amount of the *beta phase* which may then be transformed by heat-treatment at lower temperatures into the *alpha* and *delta* constituents. The equilibrium diagram mentioned also shows that the *delta phase* is stable below 570° C. only in the case of alloys having more than about 10 per cent of aluminium, so that alloys with 7·5 to 10 per cent of aluminium tend to become more homogeneous on prolonged heating. The subject of microstructure as affected by heat-treatment is a somewhat complex one, and space considerations will not here permit a more detailed account. For fuller information the reader is therefore referred to the lower footnote reference on page 171.

The general effect of heat-treatment upon the mechanical properties of the 90 Cu, 10 Al type of aluminium bronze is shown by the results given in Table 58.* These refer to specimens of 89·78 per cent copper and 9·96 per cent aluminium previously heated to 900° C. and slowly cooled to the quenching temperature.

Applications of Aluminium Bronzes

The aluminium bronzes, on account of their good strength properties at ordinary and elevated temperatures, combined with excellent corrosion resistance, have a wide potential range of commercial applications, although hitherto these bronzes have not been employed in this country to the same extent as in the United States and in France. With a more complete understanding of their excellent properties and of the methods of casting and fabrication, however, their advantages are becoming better known and in recent times, thanks to the publicity given to these bronzes by the Copper Development Association in this country, they are now finding numerous applications.

Among the *uses of aluminium bronze* in general engineering, mention may be made of their employment for hard-wearing gears, thrust pads, die-cast ball and roller bearing caps, for under-water high strength

* W. E. Atkins, W. Cartwright and T. Bolton & Sons, Ltd.

fittings (including use in sea-water), piston rods, pump rods, valves and valve spindles, inlet and exhaust valve seating insert rings for automobile and aircraft engines, worm wheels, turbine blading, shafts for high-speed mechanisms, sluice valves, rods and nuts, anchors for non-magnetic ships, die-cast brush holders for electrical machines, overhead wire suspension fittings for electric railways, high tensile acid-resisting bolts, nuts and sheathing for pickling equipment plant for resisting chemical attack by alkaline solutions and certain acids, products of chemical distillation, sea-water, etc.

TABLE 58

Effect of Heat-treatment on Mechanical Properties of Aluminium Bronze

Heat-treatment	Limit of Proportionality Tons per sq. in.	Proof Stress (0·1 per cent) Tons per sq. in.	Tensile Strength Tons per sq. in.	Elongation per cent on 2 in.	Brinell Hardness
Heated at 900° C. and quenched	6·4	20·8	43·4	4	255
Heated at 900° C., slowly cooled to 850° C. and quenched	5·6	20·8	39·2	3·5	240
Heated at 900° C., slowly cooled to 800° C. and quenched	5·2	19·2	38·3	2	216
Heated at 900° C., slowly cooled to 750° C. and quenched	6·4	13·5	31·0	6	179
Heated at 900° C., slowly cooled to 700° C. and quenched	4·8	11·4	33·8	11	165
Heated at 900° C., slowly cooled to 650° C. and quenched	5·6	9·6	27·5	17	138
Heated at 900° C., slowly cooled to 600° C. and quenched	3·0	7·4	27·4	19	123
Heated at 900° C., slowly cooled to 550° C. and quenched	2·8	6·6	26·3	29	115
Heated at 900° C., slowly cooled to 500° C. and quenched	2·8	8·8	19·2	5	136
Heated at 900° C., slowly cooled to 450° C. and quenched	1·4	8·3	18·1	4	142

In regard to their electrical applications, they are employed chiefly on account of their high strengths and corrosion resistance, but owing to the fact that their conductivity is not high are not employed for conductors. Brush holders, high tensile messenger wires and cables, cable fittings, bolts and nuts are among the parts used for electrical purposes.

A disadvantage of aluminium bronze is that it usually develops

surface films of high electrical resistance when used for current carrying purposes; these films tend to give rise to high electrical resistance and render jointing a matter of difficulty.

Mention may also be made of a series of aluminium bronzes for various purposes produced by the Manganese Bronze and Brass Co. Ltd., under the name of *Crotorite* bronzes. Apart from the general uses of aluminium bronzes previously mentioned, one grade, known as *Crotorite V*, is used for marine propeller shafts and stern tubes. In the hard-rolled or drawn condition this bronze has a tensile strength of 36 to 38 tons per sq. in. with 28 to 33 per cent elongation, 28 per cent reduction of area and a Brinell hardness of 140. It has good strength properties at elevated temperatures, as shown by the results given for tests on rolled bars in Table 59.

TABLE 59

STRENGTH OF CROTORITE V BRONZE AT ELEVATED TEMPERATURES

Temperature Centigrade	0·003 in. Proof Stress Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation % on 2 in.	Brinell Hardness
20°	17·0	39·0	40	120
327°	18·5	33·0	30	109
370°	14·5	25·0	60	106
460°	8·0	12·0	70	—

Aluminium bronzes *possess a pleasing colour* which, with their resistance to tarnishing under mildly corrosive influences, has led to their applications for coins, medallions, plaques, statues, ornamental grilles, fireplace surrounds, fittings and hearth furniture, both wrought and cast; also for the metal parts of imitation jewellery and vanity sets.

The aluminium bronzes have also been used for heavy-duty bearings and for worm nuts, on account of their strength and wear-resistance qualities. Typical hard wearing applications also include rolling mill universal joint segments or spindle bearings, screw-down nuts of rolling mills—which may weigh up to several hundred pounds each—gear wheels and pinions of various sizes, ranging from small gravity gears to centrifugally cast wheels for heavy reduction gears.

Nickel Bronzes

The nickel bronzes may be conveniently grouped into two classes namely, the *Low Nickel* and *High Nickel Bronzes*.

The *low nickel bronzes* include (1) the copper-tin bronzes with additions of nickel up to about 1 per cent; (2) the copper-tin-zinc bronzes with nickel up to 8 per cent and manganese to 0·25 per cent; (3) the nickel-aluminium bronzes; (4) the nickel-phosphor bronzes; (5) the lead-bearing bronzes with nickel up to about 2·5 per cent, and (6) the nickel-manganese bronzes with 2 to 3 per cent nickel and up to 2 per cent of manganese.

The addition of nickel to bronze tends to decolorize it in a similar manner to brass; to improve its corrosion resistance; to give higher tensile strength and hardness, and in general to refine the grain. In the case of lead-bearing bronzes, nickel—as stated previously—promotes better distribution of the lead particles, preventing segregation, or "lead-sweat"; in this connection 1 to 1·5 per cent of nickel is usually employed.

In general it has been found that the fluidity and casting qualities of many of the bronzes are improved by low nickel additions. In bronzes free from lead and in the presence of 0·25 manganese, higher nickel additions (up to about 8 per cent) make the bronzes susceptible to heat-treatment and impart physical properties of a high order. In this connection a nickel addition of over 4 per cent is generally required. The compositions of a number of typical low nickel bronzes suitable for high-duty service are given in Table 60,* whilst the corresponding mechanical properties and applications of these bronzes are shown in Table 61.

TABLE 60

COMPOSITIONS OF TYPICAL LOW NICKEL BRONZES

Ref.	Composition						
	Copper per cent	Tin per cent	Nickel per cent	Lead per cent	Zinc per cent	Phosphorus per cent	Manganese per cent
A	88·25	10·5	1·0	—	—	0·25	—
B	81·7	12·0	1·0	5·0	—	0·30	—
C	80·7	10·0	1·0	8·0	—	0·30	—
D	76·7	10·0	1·0	12·0	—	0·30	—
E	88·0	5·0	5·0	—	2·0	—	—
F	88·0	5·0	5·0	—	1·75	—	0·25
G	83·0	7·0	8·0	—	2·0	—	0·25
H	83·0	7·0	8·0	—	2·0	—	0·25

* "Properties of Nickel and Nickel-containing Materials" (Mond Nickel Co. Ltd.).

TABLE 61
MECHANICAL PROPERTIES AND APPLICATIONS OF LOW NICKEL BRONZES

Com-position Ref.	Mechanical Properties of Compositions (Table 60)				Typical Applications
	Yield Point Tons per sq. in.	Maximum Stress Tons per sq. in.	Elongation per cent	Brinell Hardness	
A	8–14	14–22	8–30	70–85	Sand-cast phosphor bronze castings for general purposes.
B	10–14	13–18	4–10	70–80	Heavy-duty bearing bronze (i.e. for rolling mills).
C	10–12	14–17	6–12	65–75	General purpose bearing bronze for semi-hard shafts.
D	9–12	14–17	8–13	65–75	Bearing bronze for unhardened shafts.
E	10	21	34	75	Sand-cast gunmetal castings. Valve bodies and fittings, etc.
F	23	33	17 ,	136	Sand-cast nickel bronze heated 1400° F. for 10 hours, water quenched. Reheated 500° F. for 5 hours, water quenched. High-duty gunmetal castings.
G	14	22	14	100	Sand-cast gunmetal castings.
H	26	35	1	227	Sand-cast nickel bronze, heated 1400° F. for 2 hours, water quenched. Reheated 700° F. for 2 hours, water quenched. Gunmetal castings for resisting wear.

The high nickel bronzes comprise the copper-tin alloys with 10 to 70 per cent of nickel with the occasional addition of small amounts of other elements, such as iron, manganese, magnesium, and silicon. These alloys have the structures typical of bearing metals but superior corrosion-resisting properties. Such alloys are particularly suited to hydraulic components, such as the bearing faces of sluice valves and similar parts used in contact with sea-water and other waters containing corrosive elements. The nickel bronzes of this class are considerably better in regard to corrosion resistance than gunmetal, or the phosphor, manganese and aluminium bronzes with no nickel content. *A typical high nickel bronze used for valve facings* has the following percentage compositions: Cu, 60; Ni, 30; Sn, 8; Fe, 2. The sand-cast metal has a tensile strength of 30 tons per sq. in. and

Brinell hardness of 240; the elongation, however, is so small as to be practically negligible. A group of high nickel bronzes has the following percentage composition limits: Ni, 15 to 60; Sn, 6 to 12; Zn, 1 to 2; Mn, 0·25; Mg, 0·1; Cu (the remainder).

These bronzes have (sand-cast) tensile strengths of 25 to 32 tons per sq. in., and yield points of 15 to 30 tons per sq. in.; the higher values correspond with the higher nickel content. The percentage elongations for alloys with nickel up to 30 per cent are from 10 to 3 per cent, whilst for higher nickel contents they range from 3 to $\frac{1}{2}$ per cent. The Brinell hardnesses for alloys with nickel up to 30 per cent are 120 to 140 and for nickel from 30 to 60 per cent, from 140 to 180.

These bronzes retain their strength properties to a notable degree at elevated temperatures. As cast, the hardness can be increased to 400 Brinell by suitable additions of silicon.

Nickel-aluminium Bronze

The addition of nickel to aluminium bronze not only tends to improve its mechanical properties, but owing to the fact that there is no appreciable galvanic action between this bronze and mild steel, it does not cause corrosion in the presence of sea or fresh water. For this reason such bronzes are applicable to marine purposes
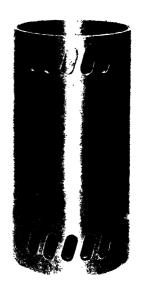
FIG. 85. NICKEL-BRONZE CYLINDER LINER FOR HIGH-PRESSURE FEED WATER HEATER

(*J. Stone, Ltd.*)

for bearings, sea-cock castings, sluice-valves, etc., attached to steel hulls of ships. It is also particularly well suited for stern tube bearings and fittings.

A *typical nickel-aluminium bronze* has the following percentage composition: Ni, 3 to 5; Al, 9 to 10; Fe, up to 5; Mn, up to 1·0; Cu (the remainder). Sand castings of this alloy have a yield point of 17 to 22 tons per sq. in. and tensile strength of 35 to 44 tons per sq. in. with 30 to 15 per cent elongation and a Brinell hardness of 120 to 150.

When *heat-treated* by quenching from 850° C. and reheating at 600° to 650° C. the alloy has a yield point of 25 to 30 tons per sq. in. and tensile strength of 44 to 50 tons per sq. in., with 15 down to 5 per cent elongation and a Brinell hardness of 150 to 200.

Nickel Bronzes for Steam and High Pressure Purposes

Nickel is used in certain types of bronze employed for parts which are to be subjected to the erosive and corrosive action of steam. The value of the nickel in such instances is due to its effect in refining the structure of the alloy. Nickel also assists the bronze to retain its
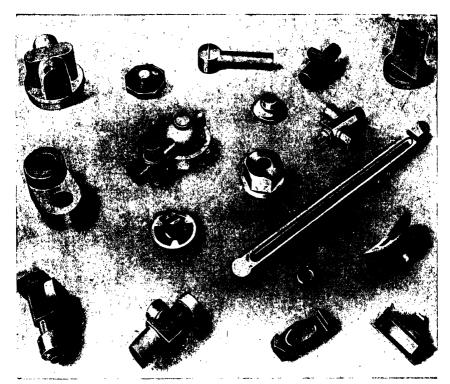
FIG. 86. EXAMPLES OF BRONZE STAMPINGS AND PRESSINGS
(*Delta Metal Co.*)

mechanical properties at higher operating temperatures to a greater extent than ordinary bronze. A further useful effect is that the addition of nickel increases the temperature range within which the alloy can be poured successfully. In general the amount of nickel added to steam bronzes varies from 1 to 10 per cent. Table 62 shows the chemical compositions of typical steam bronzes.

Nickel bronzes suitable for withstanding very high hydraulic or steam pressures have an exceedingly fine structure due largely to the

TABLE 62

COMPOSITIONS OF STEAM BRONZES WITH NICKEL CONTENT

Alloy used for	Ni	Cu	Zn	Sn	Pb	Other Elements
Large valve seats and for super-heated steam .	10	80	...	10	-	
High-pressure valves . .	3	85	2	10	- -	
Valves and seats in steam tur-bines . .	5·5	83	2	9	---	Phosphor copper 0·5
General steam bronze . .	1·5--2·5	82 -85	4--6	4- 6	3--5	Deoxidized with phosphor copper

presence of the nickel; the latter does not exceed 1·5 per cent as no increase in density occurs beyond this limit.

The percentage compositions of two typical hydraulic bronzes are as follows—

TABLE 63

COMPOSITIONS OF HYDRAULIC BRONZES

Element	Cu	Ni	Sn	Zn	Pb
Bronze A . .	84·5	0·75–1·0	2·5	7	5
Bronze B . .	87–89	1·0	6·5--7·0	1·5–3	1·5

Bronze B is used for large hydraulic castings, a typical example being that of a casting weighing 1½ tons to withstand water pressures of 2000 to 3000 lb. per sq. in. This alloy has a tensile strength of 19 tons per sq. in. with a percentage elongation of 21 to 28.

Nickel Bronzes at Elevated Temperatures

Reference has been made previously to the relatively high mechanical properties of nickel bronzes• at elevated temperatures. In this connection some comparative results for high and low nickel bronzes and a plain nickel-free bronze or gunmetal are given in Fig. 87.* The results show the low nickel bronze has 37 per cent greater strength

* "Nickel Bronze in Marine Engineering" (Mond Nickel Co. Publication).

and four times the ductility of the gunmetal at 427° C. The high nickel bronze has almost twice the tensile strength of gunmetal at room temperature and over three times at 427° C. The percentage elongation, however, is slightly lower than for gunmetal at the latter temperature.

The coefficients of linear expansion for the gunmetal, low and high nickel bronzes are 0·000018, 0·000018, and 0·000017 respectively.
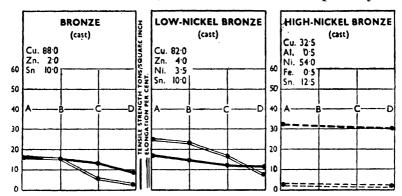
FIG. 87. NICKEL EFFECT IN PROMOTING STRENGTH AND TOUGHNESS
TO BRONZE. AT ELEVATED TEMPERATURES

A—room temperature. B—205° C. C—315° C. D—427° C.

Silicon Bronze

Copper-silicon alloys, known as silicon bronzes, are now employed commercially on account of their good mechanical properties and the *readiness with which they can be welded.*

A typical percentage composition is as follows: Cu, 94; Si, 4; Zn, 2. The cast metal has an elastic limit of 5 tons per sq. in., and tensile strength of 16 to 22 tons per sq. in., with 25 to 10 per cent elongation and Brinell hardness of 100 to 120. The melting point is about 950° C.

A typical commercial silicon bronze* recommended for parts subject to shock loads and abrasion and for the manufacture of high-speed shafts, bearing strips and pump barrels has a tensile strength in the extruded condition of 40 to 42 tons per sq. in. with 25 to 20 per cent elongation and a Brinell hardness of 170.

Beryllium Bronze

This alloy contains about 2·25 per cent beryllium and the rest copper. It is similar to a high strength phosphor bronze and is frequently

* "Silicon Bronze S.A.3," Manganese Bronze and Brass Co. Ltd.

used in the strip or wire form for springs and in sheet form for instrument diaphragms. It is also applicable in the cast or wrought state to bearings that are used under high-pressure loadings.

The copper-beryllium alloys containing more than about 1 per cent of beryllium can be hardened by quenching and reheating. Thus, the 2·25 per cent alloy is heated to 800° C. and quenched and then hardened

FIG. 88. TEST SPECIMENS OF MALLEABLE BRONZE, SHOWING RESULTS OF
HOT-WORKING TESTS
(*Delta Metal Co.*)

by a subsequent precipitation treatment for a controlled period at 250° to 300° C.

The properties of a number of beryllium bronzes in the quenched, heat-treated and work-hardened conditions are given in Table 64.*

It will be noted that by suitable treatment tensile strengths up to 85 tons per sq. in. have been obtained, but with low percentage elongations. The high values of the yield point, namely, up to 71·2 tons per sq. in., are also characteristic of these alloys. These exceptional strength properties, combined with excellent cold and hot corrosion resistance, render the beryllium bronzes *particularly suitable for spring purposes*; such alloys are much superior to phosphor bronze. As an example of their application mention may be made of a 1·5 per cent beryllium alloy† subjected to heat-treatment and cold-working in wire form which gave a tensile strength of 85 tons per sq. in. The

* "Beryllium and Beryllium Alloys," W. Hessenbruch. *Metallwirtschaft*, 20th May, 1938.

† "Beryllium in Automobile Production," *Automotive Industries*, 18th February, 1939.

TABLE 64

PROPERTIES OF COPPER-BERYLLIUM ALLOYS

Alloy	Condition	Yield Point Tons per sq. in.	Tensile Strength Tons per sq. in.	Elonga-tion Per cent $l = 10d$	Brinell Hardness	Specific Gravity
Be-Cu (α) 1·0% Be	Quenched . . .	9·5	19–22·2	50–55	65–70	
	Quenched and heat-treated	25·4	28·6–31·7	30–35	125–130	
	Quenched and work-hard-ened . . .	45·7	47·6	6	200	8·6
	Quenched, work-hardened and heat-treated . .	41·3	54·0	12	230–240	
Be-Cu (α) 2·0% Be	Quenched . . .	17·8	31·7–33·0	60–62	100–120	
	Quenched and heat-treated	63·5	69·8–76·2	3–4	330–360	
•	Quenched and work-hard-ened . . .	51·4	54·0	6	220	8·3
	Quenched, work-hardened and heat-treated . .	66·6	79·4	5	365	
Be-Cu(α + β) 2·4% Be	Quenched . . .	21·0	36·2–39·4	30–35	110–130	
	Quenched and heat-treated	66·6	76·2–82·5	3–5	340–370	
	Quenched and work-hard-ened . . .	57·8	60·3	3	230	8·2
	Quenched, work-hardened and heat-treated . .	71·2	85·7	4	375	

[Modulus of rigidity is 2860 tons per sq. in.]

2·5 per cent alloy gave similar high strength and elastic limit, with a relatively low modulus of rigidity, and could be loaded statically to 45 tons per sq. in. without showing permanent set.

The resistance to fatigue, shock and wear of beryllium bronzes is very high. Laboratory tests have shown that the fatigue limits of the heat-treated and cold-worked alloy are of the order $\pm$ 15·5 to $\pm$ 18·0 tons per sq. in., values which are about 60 per cent higher than for hard-drawn phosphor bronze as used for springs.

Beryllium bronzes are also used for *electrical contact clips and brushes,* spring washers, precision bearings and bushings, small gears and welding electrodes. A typical use for beryllium bronze springs is that for contact spring purposes in the Burgess Micro switch where the spring has withstood 10 million flexures without loss of tension and without permanent set.

The 2 to 2·5 per cent alloys, with small additions of iron and nickel, are used for electric switch points by the Chrysler Corporation. Another application is for slow-break switches to control the heater elements of electric cooking ovens, where this alloy has been found to give superior results to any other alloy previously known. Owing to the high copper content these alloys have very good electrical conductivities, namely, from 30 to 40 per cent of high conductivity copper, and they are being employed to an ever-increasing extent, notably in the

United States, *for electrical components* such as switch blades, fuse clips, plug clips, contact vibrator arms, plate, strip and wire parts, etc. Their excellent fatigue and wear resistance are further advantages in such applications. Beryllium bronzes as bearing metals are referred to in Chapter VII. In addition to its use for springs beryllium bronze
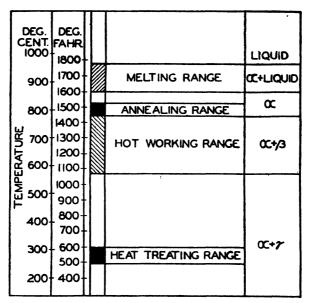
FIG. 89. TEMPERATURE RANGES FOR FABRICATION AND HEAT-TREATMENT
OF BERYLLIUM BRONZES

is also employed on account of its *non-sparking property* for tools used in explosive and chemical factories.

Toothed gears of beryllium bronze, on account of their high resistance to wear, are made from the forged and heat-treated alloys.

In regard to the *corrosion* of these bronzes tests have shown that their resistance to sea-water is good and they suffer little attack by dilute hydrochloric and acetic acids, but are affected appreciably by nitric and sulphuric acids, caustic soda and ammonia. It has also been shown* that there is no diminution in the endurance of beryllium bronze in salt spray and that in corrosion fatigue resistance *beryllium bronze is superior to most stainless steels*. The resistance to oxidation is also very satisfactory, small percentages of beryllium reducing considerably the rate of oxidation of copper; the best results appear

* H. J. Gough and D. G. Sopwith, *Journ. Inst. of Metals*, 1937.

to be obtained with the 2 per cent beryllium alloy which gives about the same rate of oxidation at 810° C. as stainless steel.

Heat-treatment of Beryllium Bronzes

It has been shown that the mechanical properties are influenced largely by the heat-treatment to which the alloy is subjected and by
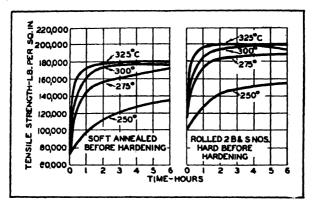
FIG. 90. STRENGTHS OF PRECIPITATION-HARDENED BERYLLIUM BRONZES AT ELEVATED TEMPERATURES

cold-working. In the former connection the range of temperatures concerned in the fabrication and heat-treatment of beryllium bronzes is shown in Fig. 89.*

The strengths of precipitation-hardened alloys of Anaconda copper-beryllium made for commercial purposes by the American Brass Co. are shown in Fig. 90, from which it will be noted that the higher temperature, namely, 325° C., gives the highest tensile strength values.

* *Ante,* page 185, note (lower reference).

CHAPTER VI

NICKEL AND ITS ALLOYS

NICKEL is one of the most important metals used in engineering, since it enters into the composition of a wide range of modern alloys and has a marked influence upon their physical and mechanical properties. Nickel occurs in nature in combination with other metals and elements, chiefly in association with arsenic and/or sulphur as *Nickel Glance* ($Ni_2(AsS)_2$), *Kupfer-nickel* (Ni_2As_2), *White Nickel* ($NiAs_2$), *Nickel Blende* (NiS) and in association with cobalt in *Spiess*. The main nickel ores are the sulphides, chalcopyrite, etc.

Nickel is extracted from its ores by several different processes, both chemical and electrolytic, of which the Mond method is employed largely on a commercial scale. It consists in passing carbon monoxide over reduced nickel oxide—obtained from its ores by a preliminary roasting process in which the sulphur is burnt off. The nickel is then taken up by the carbon monoxide to form *nickel carbonyl* ($Ni(CO)_4$), a volatile compound which is led through heated tubes. This decomposes the compound into carbon monoxide and metallic nickel. More nickel is, however, produced by the electrolytic than by the Mond process.

Properties of Nickel

Nickel is a lustrous white metal, slightly darker than silver and capable of a high polish; for this reason it is widely used as a coating for other metals, such as steel, copper, brass, etc., for both decorative and corrosion protection purposes.

It is both ductile and malleable. It is magnetic at normal temperatures, but loses its magnetic properties when heated above 340° C.

Nickel under moist air conditions tarnishes slowly and becomes covered with a film of oxide.

The commercial or malleable nickel contains small proportions of manganese and magnesium; carbon, arsenic and sulphur are harmful to the ductility and malleability of nickel and are either eliminated or kept down to extremely low percentages. The magnesium content, if properly regulated, frees the molten metal from occluded gases and improves the malleability and ductility so that the metal can be rolled into thin sheets and drawn into wire down to 0·0005 in. diameter.

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Physical Properties

Nickel has a specific gravity of 8·85. The atomic weight is 58·68. The melting point is 1452° C. (2646° F.).

The specific heat from 20° C. to 400° C. is 0·130 and from 0° C. to 100° C. is 0·1147 C.G.S. units.

The coefficient of linear expansion from 25° C. to 100° C. is 0·000013 and from 25° C. to 300° C., 0·0000145.

The thermal conductivity from 20° to 100° C. is 0·1428 C.G.S. units.

The electrical resistivity at 0° C. is 10·9 microhms per cm. cube.

The coefficient of electrical resistivity is 0·0041 per degree C. (or 0·0024 per degree F.).

The magnetic transformation point occurs at 340° C. (644° F.).

The optical reflectivity of polished nickel is 65·5 per cent for incident light of 0·589 μ wavelength.

Nickel has a higher electrical resistance than most other common metals. Thus, if the resistance of a silver wire of given length and sectional area be represented by 1·0, the respective resistances for copper, aluminium, iron, platinum and nickel are given by the values 1·047, 1·75, 7·12, 7·45 and 8·0.

Malleable nickel successfully resists attack by alkalis and is widely used in industrial processes for alkali solution containers, autoclaves and tank linings, more particularly for caustic soda. Nickel offers a good resistance to attack by hydrochloric, hydrofluoric and many organic acids. It is used for foodstuff containers where the presence of copper would cause contamination.

The *annealing temperature* lies between 750° C. and 850° C.

The *forging temperature* is 1100° C. to 1250° C.

Mechanical Properties

Malleable nickel has the properties given in Tables 65, 66, and 67.*

Machining and Working Malleable Nickel

This metal can readily be machined with high-speed tool steels, using only slight variations in the tool cutting angles, speeds and feeds used for mild steels. The cutting angles should, however, be rather sharper and the cutting speeds can profitably be made higher with suitably designed and sharp-edged tools.

For drilling purposes standard twist drills as used for mild steel are quite satisfactory.

The milling cutters employed are of high-speed tool steel with

* H. Wiggin & Co., Ltd.

TABLE 65

STRENGTH PROPERTIES OF MALLEABLE NICKEL

Condition	Proportional Limit	Yield Point	Tensile Strength
	Tons per square inch		
Rolled and annealed . . .	7·5–10·3	9–13	29–33
Cold or hard rolled . . .	Up to 33	Up to 45	Up to 63
Cast	—	9–13	27–31

Condition	Elongation on 2 in. per cent	Reduction in Area per cent	Endurance Limit Tons per sq. in.
Rolled and annealed . . .	43–53	65 75	11–14
Cold or hard rolled . . .	—	—	17–19
Cast	15–35	30–50	—

TABLE 66

HARDNESS OF MALLEABLE NICKEL

Condition	Brinell No. (3000 kg. Load) 10 mm. Ball	Scleroscope	Rockwell B.
Rolled and annealed . . .	75–95	12–14	50–60
Cold or hard rolled . . .	Up to 150	Up to 40	Up to 100
Cast	80–125	—	50–60

TABLE 67

MALLEABLE NICKEL DATA

Modulus of elasticity in tension . . .	29,000,000–31,000,000 (lb. per sq. in.)
Modulus of elasticity in torsion . . .	9,500,000–10,500,000 (lb. per sq. in.)
Pattern-makers shrinkage	¼ in. per foot
Forging and rolling temperature range . .	850°–1240° C. 1600°–2300° F.
Annealing temperature range . . .	600°– 900° C. 1100°–1650° F.

normal spacing and tooth design. For plain milling cutters the teeth should be ground at a slight taper or side clearance with the widest part at the cutting edge in order to prevent binding or tearing of the metal; the teeth should have an undercut or rake.

In regard to the tapping of nickel there is a tendency for the tough chips to jamb in the flutes of the tap so that it is advisable to use taps

FIG. 91. LABORATORY UTENSILS IN NICKEL

having two or three lands and shallow flutes, with a lip ground at the back of the cutting edges, for chip clearance; a cutting speed of 15 to 20 ft. per min. is recommended.*

Nickel sheet, although tougher than brass or aluminium, can be spun in the lathe to simple shapes but not to difficult ones. The chief drawback experienced in spinning the metal is the work-hardening effect which toughens the metal appreciably.

Nickel can be forged without difficulty by hand or die methods in a somewhat similar manner to steel if the correct forging temperature, mentioned previously, is employed.

Nickel can be soft-soldered, silver-soldered and *brazed* as readily as copper, using the same solders and fluxes.

* H. Wiggin & Co., Ltd.

Nickel can also be welded by the oxy-acetylene and electric welding methods. For oxy-acetylene welding the flame must be of the reducing type, i.e. with excess of acetylene. Powdered boric acid should be used as a flux. For metallic arc welding the nickel should be the *negative* electrode and a suitable deoxidizer and flux coating used on the electrode. The slag should float readily on the top of the metal and protect it against oxidation.

Nickel can be rolled on to steel to form nickel-clad plate or strip.*

FIG. 92.   PHOTOMICROGRAPH SHOWING A TYPICAL NICKEL TO STEEL BOND
× 200

The nickel layer is firmly adherent (Fig. 92) and the compound sheet can be fabricated in a similar manner to ordinary steel plate. It is used in the construction of industrial chemical tanks, kettles, containers, etc.

Nickel Alloys

Nickel alloys include a wide range of great importance in engineering and industry on account of their high mechanical strength properties, corrosion resistance, electrical qualities, decorative applications, etc.

The ferrous alloys, which are dealt with more fully in Volume I of this work, include the high tensile nickel and nickel-chrome steels, heat-resisting steels, improved and high-duty cast irons, heat-resisting cast irons, tool steels, etc.

* Nickel-clad plate and nickel-coated strip are dealt with in Vol. I of this work.

In addition there is a group of ferro-nickel alloys which includes the low thermal expansion alloys, e.g. *Invar* and *Elinvar*; the high nickel series of high magnetic permeability at low magnetic field intensities, e.g. *Permalloy* and *Mumetal*, and the non-magnetic cast irons, such as *Nomag*.

Another group of nickel alloys includes the *high-strength nickel brasses* and *bronzes*.

In the electrical field, apart from the ferrous alloys mentioned previously, there are the magnet steels containing nickel, such as
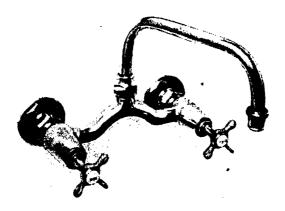
FIG. 93. NICKEL SILVER MIXING TAP UNIT (20% NICKEL-SILVER)

Alnico and *Alni*, which represent about the best of present magnet steels. There is also an important range of nickel-chromium high resistance alloys such as *Dullray, Glowray, Brightray*, etc.

Nickel is also a constituent in certain high-strength aluminium alloys, including *Y-alloy* and *R.R. alloys*.

In the nickel-copper range of alloys there are several important ones including those used for corrosion-resisting condenser tubes; resistance alloys such as *Constantan, Ferry* and *Eureka*; *Monel metal*, alloys used for bullet envelopes, etc.

For decorative purposes certain nickel content alloys, such as *Nickel Silver* and *Silveroid*, have numerous industrial applications. Nickel is also a useful item in the composition of certain lead-bronzes employed for high-duty bearings in aircraft and automobile engines.

In association with chromium and iron nickel forms an important alloy, known as *Inconel*, having excellent mechanical strength, corrosion-resistance and heat-resistance properties.

An alloy of nickel and chromium with a high nickel content, known as *Brightray*, is used for facing the exhaust valves of high-performance engines, e.g. aircraft engines.

There are many other alloys containing nickel which it is not possible to refer to in this brief survey, but some of these are mentioned later in this volume in the appropriate sections.

Nickel-beryllium Alloys

Nickel alloys containing up to 2 per cent beryllium are employed in the U.S.A. as spring material and bushings. When suitably heat-treated from rolled material the alloys have a tensile strength of about 115 tons per sq. in., and possess a high fatigue resistance. They have been used in Germany for aircraft engine valve springs.

In connection with these alloys it has been found* that the addition of a third element, such as titanium, iron, manganese, or molybdenum, leads to equivalent hardening properties at a beryllium content considerably below that of the binary alloys.

A typical binary alloy of nickel with 2 per cent beryllium has the strength properties shown in Table 68,† whilst a small addition of titanium gives the strength values shown in the same Table.

TABLE 68

MECHANICAL PROPERTIES OF NICKEL-BERYLLIUM ALLOYS

Alloy	Condition	Yield Point Tons per sq. in.	Tensile Strength Tons per sq. in.	Elongation per cent on 10 cm.	Brinell Hardness
Be-Ni 2% Be	Quenched	22·8	50·8	48	140
	Quenched and heat-treated .	50·8	82·5	20	420
	Quenched and work-hardened	95·3	101·6	1·5	360
S.G. = 8·1	Quenched, work-hardened and heat-treated . . .	95·3	117·5	8	480
Be-Ti-Ni	Quenched	25·4	54·0	40	150
	Quenched and heat-treated .	50·8	88·9	1·5	440
S.G. = 8·1	Quenched and work-hardened	98·5	104·5	1	360
	Quenched, work-hardened and heat-treated . . .	98·5	120·5	5	500

* " Beryllium and Its Alloys," H. A. Sloman, *Metal Industry*, 23rd February, 1934.

† *Ante*, page 185, note (upper reference).

The exceptionally high tensile strengths and hardnesses of the heat-treated and work-hardened alloys rival those of some of the alloy steels; in addition the high degree of corrosion resistance and also resistance to oxidation up to 700° C. to 1000° C. render them suitable for high-strength purposes at normal and elevated temperatures.

A commercial alloy used in the United States has the following percentage composition: 0·6 to 1·0 Be; 7·0 Mo; 15 Cr; 60·0 Ni; iron (the remainder). The tensile strength of this alloy can be more than doubled by quenching from the solid solution condition to the softest state, then cold-working and reheating to a moderate temperature. In this way the tensile strength has been increased from 51·5 tons per sq. in. in the soft state to 116 tons per sq. in. by heat-treatment, hard rolling and reheating; the Brinell hardness increases from 140 to 460 by these operations.

The alloy mentioned, but without the addition of the beryllium, is known commercially as *Contracid* on account of its corrosion resistance properties.

In the alloys with a nickel-chromium base, results of considerable practical importance have been obtained by the addition of beryllium to corrosion and heat-resisting alloys. This is true also of those which in addition contain molybdenum. Hardness values of a high order are obtainable and these properties are stable over a wide range of temperatures. The high temperature tensile properties and creep strength are very satisfactory. Applications of these alloys include high-temperature springs, surgical instruments and engine valve springs.

The Nickel-copper Alloys

Nickel forms with copper in varying proportions a continuous series of solid solutions without any intermetallic compounds or double phase products.

Fig. 94 shows the liquidus and solidus curves* for the series of alloys from which it will be seen that the melting points rise uniformly from that of copper, namely, 1083° C. (1982° F.), to that of nickel, namely, 1452° C. (2646° F.). In this connection the alloys of nickel and copper differ from those of copper and zinc (the brasses) and tin (the bronzes) in having higher melting points than that of copper itself. It follows from this that when casting nickel-copper alloys furnaces which only just serve for the brasses will be unsuitable, without modification.

* Guertler.

Heat-treatment and Fabrication

The nickel-copper alloys can now readily be produced *in fabricated forms*, but the presence of carbon and sulphur causes embrittlement; in this connection the addition of manganese up to 1·0 per cent is advocated. *The annealed metal* is employed for sheet metal and similar fabricated forms, annealing being effected at 550° C. to 750° C.; the
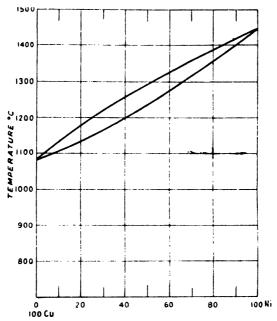
Fig. 94. Liquidus and Solidus Curves for Nickel-copper Series

lowest temperature at which the metal will soften should be used in each instance, since any carbon present is liable to precipitate at high temperatures. To avoid scaling the annealing should be done in closed pots or in an inert atmosphere; the cooling rate is more or less immaterial.

Mechanical Properties

The nickel-copper alloys containing nickel up to 50 per cent show a gradual increase in tensile strength, almost in proportion to the nickel content, together with an increase in the elastic modulus, as shown by the results given in Table 69.*

* *The Nickel-copper Alloys*, Bureau of Information on Nickel.

TABLE 69

MECHANICAL PROPERTIES OF NICKEL-COPPER ALLOYS

Nickel, per cent	Tensile Strength (Tons per sq. in.)	Modulus of Elasticity (Tons per sq. in.)
0	20·6	7080
10	27·9	7600
20	34·4	8000
30	42·0	8580
39·7	45·8	9240
45·6	51·6	9470

The addition of nickel to copper, even in very small amounts, has a marked effect upon its mechanical properties. Thus the addition of 2 per cent of nickel increases the tensile strength slightly and improves the ductility considerably.

The following values are given by Hughes for the 2 per cent alloy: Tensile strength, 15·2 tons per sq. in.; elongation on 8 in., 49·0 per cent, and reduction of area, 78·2 per cent. These values refer to the cold-rolled metal after annealing. The toughness or impact value of the alloy is also rapidly improved. Thus, the addition of 1·5 per cent of nickel to copper doubles the impact value. The nickel-copper alloys containing from 15 per cent nickel and upwards are notable for their combined ductility and toughness. For this reason such alloys are used for making *bullet envelopes* since they can be cold-worked to a very marked degree.

The 20 per cent nickel alloys are among the most ductile non-ferrous alloys in commercial use. They may be cold-rolled from 1½ in. down to 0·01 in. without annealing, while the following figures (the mean of two tests) given by 80/20 copper-nickel wire obtained by cold-rolling a 2 in. diameter bar to ⅝ in. and then cold-drawing to 0·02 in., all without annealing, show that even after this drastic treatment, resulting in a high maximum tensile strength, appreciable ductility is still retained.

Maximum Stress   .   .   .   .   57·0 tons per sq. in.
Torsion turns per 100 diameters .   .   37

The strength properties of three typical copper-nickel drawn rods, containing respectively 15, 20 and 40 per cent of nickel, are given in Table 70.*

In the case of hard-drawn nickel-copper wires the tensile strengths of 15, 20 and 40 per cent nickel content wires of 10 S.W.G. were

* Bureau of Information on Nickel.

TABLE 70

Strength Properties of Nickel-copper Drawn Rods

Composition		Condition	Tensile Strength Tons per sq. in.	Elonga- tion per cent	Reduction of Area per cent
Nickel	Copper				
15	85	HARD . . .	31·7	17·0	73·4
		Annealed 850°-900° C. for 15 minutes . .	20·5	50·0	86·5
20	80	HARD . . .	33·5	18·0	70·0
		Annealed 850°-900° C. for 15 minutes . .	21·4	51·0	83·6
40	60	HARD . . .	40·9	12·0	56·6
		Annealed 850 -900° C. . .	26·7	44·8	73·0

34·8, 36·5 and 40·6 tons per sq. in. respectively; the corresponding elongations were 6·25, 5·1 and 4·7 per cent respectively.

Tensile strengths up to 50 tons per sq. in. have been obtained with hard-drawn wires of 40 per cent nickel-copper alloy for wires of 18 to 20 S.W.G.

The 20 per cent nickel-copper alloy used for bullet envelopes has a tensile strength of about 40 tons per sq. in. in the sheet form, as received from the manufacturers. By annealing at temperatures of 300°, 500°, 700° and 750° C. for periods of 3 hours each, the respective tensile strengths are 38·2, 25·5, 23·5 and 23·1 tons per sq. in. The percentage elongations were 8·5, 34·0, 38·0 and 44·0 respectively; these values show the marked effect of annealing upon ductility. The percentage reduction of area values in the above examples were 36·0, 53·5, 61·5 and 63·0 respectively.

Strengths at Elevated Temperatures

It is characteristic of the nickel-copper alloys that they retain their strength properties at temperatures well above normal. Thus in the case of the 12 per cent nickel alloy the tensile strength of a specimen tested at 13° C. was 18·1 tons per sq. in., with 55·5 per cent elongation and 63 per cent reduction of area.

As the temperature was increased these values all fell progressively until at 455° C. they reached the values of 9·9 tons per sq. in., 27·5 and 41·0 per cent respectively.

Some comparative temperature-strength results for the 80/20 and 98/2 copper-nickel alloys and typical brasses, bronzes and gunmetal

are given in Fig. 95. It will be observed from these results that both of the copper-nickel alloys compare very favourably with the best of the bronzes and brasses; the 80/20 alloy is actually stronger above 325° C. than any of the other materials tested; the 98/2 alloy is stronger above 410° C.

Other Nickel-copper Alloys

In connection with the alloys containing less nickel than copper, the 2 per cent nickel-content alloys are used for locomotive stay rods
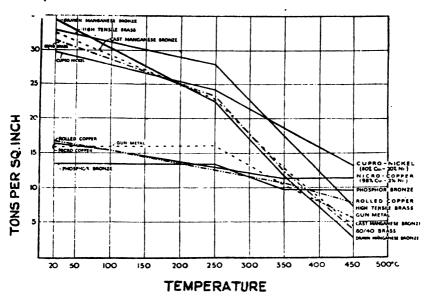
FIG. 95. PROPERTIES OF NICKEL-COPPER AND OTHER ALLOYS AT
ELEVATED TEMPERATURES

and boiler and flue tubes. This alloy has also been much used for the driving bands of shells.

An important application of alloys with 15 per cent and upwards of nickel is for condenser tubes, as these alloys exhibit marked resistance to corrosion : after long periods of service such tubes show little if any corrosion whereas the brass tubes previously employed would be rendered useless in one-quarter to one-sixth of the period (Fig. 96).

The tendency, in marine work, is to use alloys of higher nickel content, namely, at least 30 per cent, as such alloys under severe working conditions in marine condensers stand up extremely well over long periods.

Another advantage of this group of alloys is their immunity from the defect known as "season cracking."

The alloys with 40 to 45 per cent nickel are much used for *electrical purposes* on account of their low temperature coefficients and high
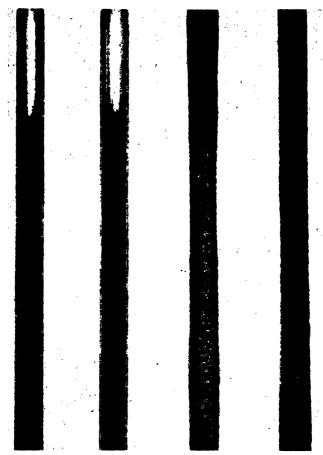
FIG. 96. SHOWING (*Right*) CORRODED BRASS CONDENSER TUBES WITH LESS THAN ONE YEAR'S SERVICE, AND (*Left*) CUPRO-NICKEL TUBES AFTER FOUR YEARS' SERVICE

resistivity, combined with corrosion resistance, so that they are employed for resistance and rheostat elements. Another application is for *thermo-couple pyrometers*, in conjunction with copper and iron as the other elements. Typical resistance alloys of this class are

Constantan, Ferry, and *Eureka. Constantan* contains about 40 per cent nickel and 60 per cent copper. It has an electrical resistance about 25 to 30 times as great as copper, the actual value being about 50 microhms
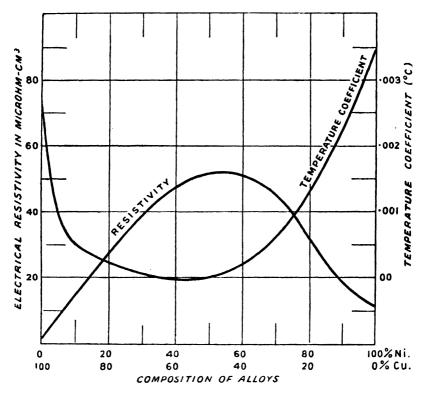
FIG. 97. ELECTRICAL RESISTANCE PROPERTIES OF NICKEL-
COPPER ALLOYS

per cu. cm. at 20° C. The coefficient of resistance increase with temperature is 0·000005 per deg. C. at 20° C.

The thermo-electric power with copper (for thermo-couples) is 40 microvolts at 0° C. The specific gravity is 9·73.

Other high-resistance nickel alloys are *Nickeline* (25 per cent nickel) and *Manganin* (an alloy of copper, nickel and manganese).

The group of alloys having 45 per cent of nickel and above are also employed, on account of their silvery-white appearance and non-corrosion properties, for various *decorative and domestic purposes.* In cafeteria work they are used in the sheet form for counter tops and

soda fountain parts. The resistance of these alloys to attack by vegetable and fruit acids has resulted in their employment for spoons, forks and containers and also for vessels employed in various chemical, semi-chemical and food preparation industries.

Other applications of this group of alloys include those of radiator shell pressings, automobile fittings, ships' furniture fittings, and those
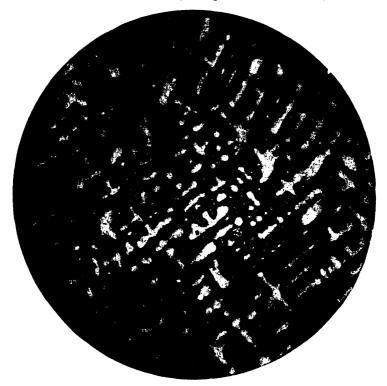
FIG. 98. SHOWING STRUCTURE OF CAST MONEL METAL

for architectural purposes, e.g. door furniture, staircase rails, grilles and lift doors.

Hitherto, we have dealt with nickel-copper alloys having less nickel than copper, but as the nickel content is increased above 50 per cent there is some improvement in the mechanical strength properties, though the range of alloys between 60 and 80 per cent nickel give the optimum strength figures; on either side of this range there is a falling off in strength. The 65 to 70 per cent nickel-copper alloy with low iron content is the well-known Monel metal used commercially for various

purposes. It should be here noted that variations other than those in nickel content may affect the properties of the alloys in this range appreciably. Carbon, in particular, has a marked influence on the mechanical properties and must therefore be kept below about 0·25 per cent.

Monel Metal

Monel metal is the name given to a high nickel-copper alloy widely employed commercially on account of its good mechanical and corrosion resistance properties. It has the following limits of percentage composition, namely: Ni, 65–70; Cu, 26–30; Fe, to 3·0; Mn, to 1·5; Si, to 0·25; C, to 0·25.

In the case of castings these may have a higher silicon content up to about 4 per cent. It may be mentioned that silicon-content Monel castings have more recently been produced which can be heat-treated; normally Monel is not responsive to heat-treatment, but can be hardened by mechanical working.

In regard to the structure of Monel, as this is composed principally of nickel and copper the physical properties are those typical of the solid solution. The structure of cast Monel is shown in Fig. 98. Once this structure or "cored" formation has been broken down by forging, rolling or cold-working the grain size is reduced and rendered more uniform as illustrated by the three illustrations given in Fig. 99.

Physical Properties

The principal physical properties of Monel are as follows*—

Density . . . . 8·80
Lb. per cub. in. . . . . . . 0·318
Melting point . . . . 1350° C. (2460° F.)
Specific heat (20°–400° C.) . . . . 0·127
Coefficient of expansion (25°–100° C.) . . 0·000014
per 1° C.   (25°–300° C.) . . . 0·000015
Heat conductivity (0°–100° C.): ⅕ that of Commercial Copper.
Electrical resistivity (at 0° C.)—
    micro-cm.³ . . . . . . 42·5
    ohm-mil-ft. 256
Magnetic transformation . . . . 95° C. (203° F.)
Recrystallization temperatures† (lower limits) . 430°–820° C.

Mechanical Strength Properties

The tensile strength and elongation of Monel cover a wide range depending upon the condition, i.e. whether as cast, annealed, hot or

* H. Wiggin & Co. Ltd.
† Dependent upon grain size.

(a)
Excessive grain size due
to overheating.

(b)
Cold-rolled and fully softened
by correct annealing.

(c)
Typical hot-rolled rod.
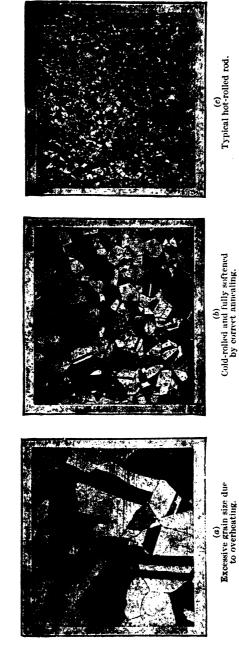
FIG. 99. MICROSTRUCTURE OF MONEL METAL

cold rolled. In general, however, the alloy has a high ductility in its wrought forms, and in this connection the ductility of Monel spring wire is such that it can be bent around its own diameter without fracture. Similarly, it has been shown that a 1-in. diameter Whitworth threaded rod can be bent back on itself, i.e. through 180° without fracture, at normal air temperature.

Monel castings have a yield point of 12 to 15 tons per sq. in. and tensile strength of 19 to 23 tons per sq. in. with about 12 per cent elongation ;* the Brinell hardness value is 110 to 130.

There is a special silicon Monel used for castings, which, upon heat-treatment, gives tensile strength values of 38 to 40 tons per sq. in. with 10 to 15 per cent elongation and a Brinell hardness of 190 to 210.

Cold-drawn bars have a yield point and tensile strength of 35 to 40 and 40 to 45 tons per sq. in. respectively, with 20 to 18 per cent elongation ;* the Brinell hardness value is 210 to 190. When annealed, however, the yield point and tensile strength fall to 14 to 17 and 30 to 35 tons per sq. in. respectively, whilst the ductility is improved, the percentage elongation being about 35, and Brinell hardness 110 to 120.

Normal hot-rolled bars have slightly higher tensile strengths and about the same ductility as the annealed cold-drawn bars.
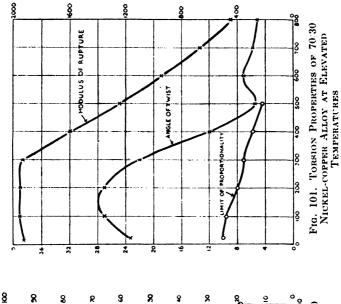
Cold-rolled sheet or strip has a tensile strength of 40 to 45 tons per sq. in. with 15 per cent elongation ; the effect of annealing the metal is to reduce the tensile strength to 29 to 30 tons per sq. in., with increased elongation of 30 per cent. The yield point of the hard cold-rolled sheet or strip has the same value as the tensile strength.

Cold-drawn wire has a tensile strength of 55 to 60 tons per sq. in. with 5 to 10 per cent elongation and a yield point of 50 to 55 tons per sq. in.; when annealed the tensile strength becomes 29 to 33 tons per sq. in. with 35 per cent elongation.

The *endurance limits* of Monel in the annealed and hot-rolled condition are about ± 16 tons per sq. in. and in the fully worked condition about ± 22 tons per sq. in.

The *Izod impact values* of hot-rolled and annealed Monel range from 115 ft.-lb. to the limits of the 120 ft.-lb. Izod testing machine. Monel cold-rolled to 50 per cent reduction has an Izod value of 65 to 80 ft.-lb.

The *modulus of elasticity* of Monel is 25 to 26 × 10⁶ lb. per sq. in.

The *modulus of rigidity* of Monel is 8 to 9 × 10⁶ lb. per sq. in.

* On 4 √area

Fig. 101. Torsion Properties of 70/30 Nickel-copper Alloy at Elevated Temperatures

Fig. 100. Mechanical Properties of 70/30 Nickel-copper Alloy at Elevated Temperatures

Strength at Elevated Temperatures

The tensile strength of Monel increases with decrease of temperature below normal atmospheric values and, in common with other alloys, decreases as the temperature is raised, but at a lower rate than that of the brasses and many of the bronzes.

Fig. 100* illustrates the mechanical properties of Monel at temperatures up to 800° C., at which temperature the tensile strength is
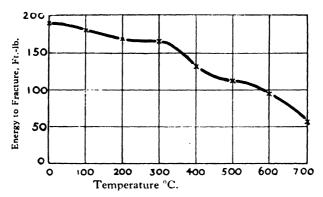
FIG. 102. IMPACT STRENGTHS OF 70/30 NICKEL-COPPER ALLOY AT ELEVATED TEMPERATURES

8 tons per sq. in. The torsional strength properties over the same range of temperatures are illustrated in the graphs given in Fig. 101.

In regard to the creep stress, the limiting values at 400°, 500°, 600° and 700° C. are given as 24, 10, 2 and 1 ton per sq. in. respectively; these limiting stress values are such that they will not cause fracture if applied continuously over a period of at least three years. At stresses lying between the limiting creep stress and the limit of proportionality the metal will deform slightly and in doing so will be work-hardened to the extent that it will resist creep at these stress values.

The impact strengths of 70/30 nickel-copper alloy at elevated temperatures are shown in Fig. 102.

Torsional Strength

The average torsional strengths of hot-rolled and cold-drawn Monel are shown in Table 71.

* "Mechanical Properties at High Temperatures of an Alloy of Nickel and Copper," H. J. Tapsell and J. Bradley, *Journ. Inst. Metals*, 1926.

TABLE 71
TORSIONAL STRENGTH OF MONEL (H. Wiggin & Co., Ltd.)

Condition	Yield Point Tons per sq. in.	Breaking Stress Tons per sq. in.	Limit of Proportionality Tons per sq. in.
Hot-rolled . . .	12–16	27–28	9–13
Cold-drawn (1 in. diameter)	33–36	40–42	20–22

Corrosion Resistance of Monel Metal

On account of its high nickel content Monel possesses excellent corrosion-resistance qualities which enable it to be used for a wide range of industrial and engineering applications.

It does not corrode under atmospheric conditions, even in air conditions of industrial centres. It is unaffected by sea and estuarine waters and for this reason is frequently employed in marine practice for propeller shafting of small boats, propellers, mast fittings of yachts, ships' bolts and nuts, galley-fittings, tanks, etc.

It is unaffected by alkaline solutions and is therefore used for evaporators and other plant in the recovery and production of caustic soda. It is attacked, however, by ammonium hydroxide solutions of over 10 per cent concentration, but not by weaker solutions.

Monel is only slightly attacked by acetic, citric and tartaric acids but is affected by nitric acid.

The acid attack increases with aeration and with hydrogen-ion concentration. Air-free acids, other than those of an inherently oxidizing character, like nitric acid, do not appear to corrode Monel, but the rate of attack may become fairly high in aerated solutions of the stronger acid and hydrogen-ion concentrations. It is not materially affected by sulphuric acid concentrations up to 80 per cent and is much used, commercially, in contact with this acid. Similarly, Monel is unaffected by pure phosphoric acid.

Monel is highly resistant to the corrosive and erosive action of superheated steam, and since it retains a marked proportion of its strength at temperatures up to about 400° C., it is particularly suited to the making of certain steam parts and fittings.

At high temperatures (450° C. to 500° C.) in oxidizing atmospheres it develops a protective oxide skin.

Fabrication of Monel Metal

Monel is *hot-forged* and worked at 1040° C. to 1150° C. and should not be hot-worked at much below the former temperature since the hot

ductility of the metal falls rapidly with temperature decrease. It loses all malleability at about 1210° C. Furnaces used for heating Monel should be of the type in which combustion occurs before the hot gases reach the metal; sulphur-free fuel should be employed. Further, a definitely reducing atmosphere is necessary to avoid oxidation and scaling.

Monel is *cold-worked* in a somewhat similar manner to mild steel for operations such as drawing, bending, die-forging, forming and pressing. Owing to its high elastic limit an appreciable amount of power is required in these operations; for this reason it is difficult to spin and fabricate by hand. Moreover, frequent annealing is required for multiple forming processes.

For wire and rod drawing it is necessary to employ chromium-plated hardened steel, tungsten carbide, or diamond dies with well polished surfaces.

Monel is annealed by heating at 900° C. to 950° C. for about five minutes. It can be box-annealed satisfactorily at 730° C. to 790° C. for about an hour.

Machining Monel Metal

This alloy can be machined either dry or with the usual lubricants provided suitable tools, speeds, and feeds are employed.

Monel metal machines with a long, tough chip, in this respect closely resembling copper, but requiring about the same power to cut as mild steel.

Cast Monel metal requires somewhat more power. Owing to the great toughness of the metal, tools with a keen edge are necessary in all machine work. These tools should be ground with a decided rake or lip, and only the better grades of high-speed steels used.

Fig. 103 illustrates the various tools recommended for machining Monel metal and other nickel-copper alloys.

In regard to the cutting speed, this will vary with the depth of cut and feed from 30 to 100 ft. per min.

Soldering, Brazing, and Welding Monel Metal

The alloys can be soft soldered or brazed quite easily as long as the usual precautions regarding cleanliness, freedom from oxide, etc., are taken. Any fuel containing a high sulphur content should be avoided. The same flux, solders, and tools are used as for copper. Any oxide on hot-worked metal should be removed before commencing to solder. Monel metal is brazed in the same manner as copper, using

ordinary solder with borax as flux. It can also be silver-soldered, using a blow-torch with the same flux.

Electric resistance welding with spot- or butt-welding machines is the same as with any other metal, while the oxy-acetylene or arc welding processes can be utilized without any great difficulty. In every case absolute cleanliness of the metal and of the welding rod, where

TURNING TOOL

SCREW-CUTTING TOOL

FOR ½ DIAMETER, OTHER
DIAMETERS PROPORTIONAL

DIES

TAP
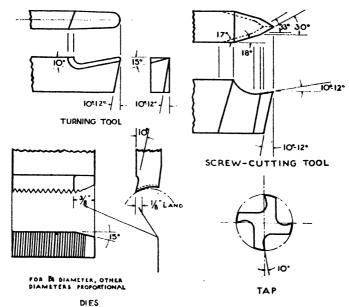
FIG. 103. TOOLS RECOMMENDED FOR MACHINING
MONEL METAL

used, is essential to success. A wash over with a strong solution of borax is often helpful.

With the oxy-acetylene process sulphur-free gas must be employed and the reducing or central part of the flame utilized. In arc welding special precautions against oxidation are necessary and the welding rods might also profitably be protected by one of the usual covers. It is important to see that the welding rod is the positive electrode, i.e. the converse of what is usual when arc welding steel.

Monel metal can be welded to cast iron, steel, brass, bronze, copper, in fact to almost any common metal or alloy.

Monel metal can be pickled in any of the normally employed sulphuric acid or hydrochloric acid solutions, provided some oxidizing agent (such as ferric oxide, sodium dichromate, etc.) is added to

prevent re-deposition of the copper from the solution on to the pickled metal.

Applications of Monel

Monel is employed for fittings and components requiring relatively high mechanical strength at normal and elevated temperatures up to about 500° C., combined with good corrosion resisting qualities. It is widely used, therefore, for industrial manufacturing tanks, kettles,
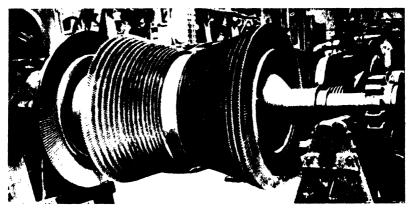
FIG. 104. TURBINE BLADING OF MONEL METAL

pumps, mixers, valves, wire-gauze strainers, tubes, diaphragms, coils for heating nuts, bolts, washers, bushings, shafts, etc.

It also finds wide application in the textile industry in connection with plant used for dyeing of fabrics and artificial silk, bleaching, mercerizing, drying and finishing machinery. It is also much used in food manufacturing plant. Its marine uses have previously been referred to and in particular its suitability for propeller shafting of small boats.

In the aircraft industry Monel has been used for the *valve seat inserts* of aluminium alloy cylinder heads, since it is considerably harder than the aluminium bronze hitherto employed and is non-corrosive to the hot exhaust gases. It has been used for *petrol pipes* in place of copper, since it offers better corrosion resistance and has higher tensile and fatigue strengths.

Other aircraft applications include wing tip floats of seaplanes, mooring buoys, Monel rivets for metal wing lattices, floats and hulls, elevating jacks of flying boat rudders, water storage tanks, etc. Monel radiators of extremely light construction, which are completely

resistant to water, lubricating oil and ethylene glycol, have been employed on continental aircraft.

Among the automobile parts for which Monel is applicable are radiator pins, body bolts, screws and nuts, licence plate bolts, and air and oil cleaner wire gauze filters. In general engineering it is employed for reciprocating pump plungers, valves, spindles, etc., and in circulating pumps used for condenser water cooling. Other uses include gland rings, springs, metal gauze filters, disc valves, governors, stop valve seats, castings, cylinder liners, bolts, studs and nuts.

In connection with high pressure super-heated steam practice, typical Monel components include valve discs and seats of soot blowers, gauge cocks, safety valves, blow-down valves, non-return check valves. It is used for seats and lids of main steam valves, as it resists the cutting action of high velocity steam, even when abrasive particles of rust or crystallized salts are present.

Monel valve stems retain a high proportion of strength at elevated steam temperatures, thus eliminating risk of breakage.

Monel is used for turbine blading as it resists the cutting action of superheated steam, retains strength and toughness at high temperatures, has inherent resistance to corrosion, and can be drawn to accurate profiles with sharp edges and smooth surfaces.

Monel steam purifier baffles are employed as they are immune from rust and corrosion and easy to fabricate.

In hydro-electric plants Monel is used for needles and nozzles controlling water jets on Pelton wheels.

Strainers of perforated Monel sheet or wire cloth are used in regulating valves, meters and on lubricating oil, steam and fuel oil lines, etc. Monel is also regularly used for ball float and other types of steam trap valves.

Corrugated Monel joint rings (Fig. 105) are practically unaffected by the cutting action of high pressure, high superheated steam, and do not blow out if a joint becomes slack.

In railway work, Monel is sometimes employed for fire-box stay bolts.

Mention may also be made of *Monel-faced plywood* which, on account of the permanent retention of its pleasing decorative appearance, is employed for shelving, doors, food service lifts, table tops, furniture, wall-panelling, cold storage construction, etc.

K-Monel

A more recent alloy, known as *K-Monel*, has been developed from Monel metal and is capable of heat-treatment so that it gives similar

mechanical properties to those of steel. This nickel alloy, which contains aluminium, obtains its full strength properties by hot or cold working and heat-treatment. It has the following percentage composition: Ni, 66; Cu, 29; Al, 2·75; Si, 0·25; Mn, 0·4; Fe, 0·9; C, 0·15.
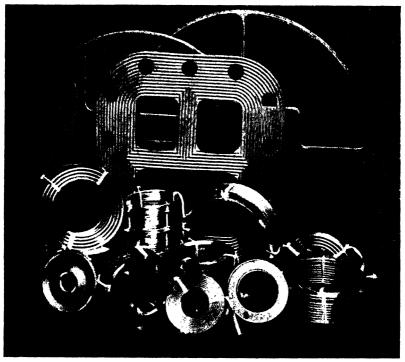
FIG. 105. A SELECTION OF MONEL JOINT RINGS
(*Metallic Manufacturing Co.*)

The alloy melts at 1315° C. to 1350° C., and has a specific gravity of 8·6.

The specific heat from 20° C. to 400° C. is 0·127.

The coefficient of linear expansion from 25° C. to 100° C. is 0·000014 per ° C.; from 25° C. to 600° C. it is 0·000016.

The thermal conductivity from 0° C. to 100° C. is 0·043 C.G.S. units.

The electrical resistivity is approximately 62 microhms per cm. cube.

The alloy is magnetic at temperatures below − 79° C., being non-magnetic above this temperature.

The mechanical strength properties in the three conditions in which K-Monel is available commercially are given in Table 72.

TABLE 72

MECHANICAL PROPERTIES OF K-MONEL

Condition	Ultimate Strength Tons per sq. in.	Yield Point Tons per sq. in.	Elonga- tion per cent on 2 in.	Izod Ft.-lb.	Brinell Hardness
Hot-rolled and softened .	39	19	35	100	140
Hot-rolled, softened, and thermally hardened .	60	43	30	70	270
Cold-worked and therm- ally hardened . .	72	60	15	50	320

The fully heat-treated metal will withstand an alternating stress of $\pm$ 17·5 tons per sq. in. for 10 million cycles without fracture.

The elastic modulus in tension is 26×10^6 lb. per sq. in. and in torsion $9·5 \times 10^6$ lb. per sq. in.

Strength at Elevated Temperatures

The values given in Table 73 refer to short-time tensile tests made upon cold-drawn and heat-treated rods—

TABLE 73

STRENGTH OF K-MONEL AT ELEVATED TEMPERATURES

Temperature °C.	Maximum Stress Tons per sq. in.	Yield Point Tons per sq. in.	Propor- tionality Limit Tons per sq. in.	Elongation per cent on 2 in.	Reduction in Area per cent
25	73·6	55·8	46·9	21·0	38·9
95	72·8	55·4	46·4	21·0	37·0
205	69·6	52·7	44·6	20·0	35·0
315	65·9	48·5	37·5	19·5	32·8
425	55·8	47·3	36·3	18·5	29·8
540	55·6	45·9	31·5	9·8	9·8

In regard to the creep strength the following results may be quoted.* Specimens of rod which had been cold-worked and heat-

* H. Wiggin & Co., Ltd.

treated to give a Brinell hardness of 285 sustained a load of 30 tons per sq. in. at 400° C. for three weeks without showing any measurable creep. In the case of fully heat-treated rod, having Brinell hardness of 240, which had not been cold-worked, a load of 20 tons per sq. in. was sustained for three weeks without showing any measurable creep.

Heat-treatment and Machining

To soften K-Monel metal, it should be heated to a temperature of approximately 900° C. for a sufficient time to ensure complete soaking, and be quenched in water or oil.

To harden, the material should be reheated to a temperature of 590° C., and slowly cooled. The degree of hardness developed varies to some extent with the time of exposure at this temperature. Four hours is generally sufficiently long to develop practically full hardness, but slightly increased hardness results from holding at this temperature for six or eight hours. The hardening treatment can be applied to softened, hot-rolled, or cold-worked material.

In the softened or moderately hardened (up to 270 Brinell) condition it can be machined at almost the same speeds and feeds as for mild steel, provided good quality high-speed steel tools are used. In the work-hardened plus thermally-hardened condition (Brinell 280–330, or even higher), Widia or similar cemented carbide tools are usually necessary, but this can be avoided by machining before final thermal hardening.

On account of its high mechanical strengths at ordinary and elevated temperatures and its corrosion resistance—which is similar to that of Monel metal—this alloy has many applications in engineering.

Typical examples are: valves and seats in pumps handling oil containing brines and sodium sulphide (here K-Monel has outlasted high alloy corrosion-resisting steels with a service life of 4 to 1 in favour of K-Monel), valves and seats on "starting-air" bottles for Diesel engines, blades for paper-making machinery, and impulse blading of steam turbines operating at high pressures and superheats.

Inconel

Inconel is another more recent alloy having excellent mechanical properties at ordinary and elevated temperatures, combined with important corrosion resistance at these temperatures. It is also amenable to fabricating operations. Inconel has the following percentage composition: Ni, 80; Cr, 14 to 14; Fe, the remainder.

It has a melting point of 1395° C. and specific gravity of 8·55.

The specific heat from 25° C. to 100° C. is 0·109 C.G.S. units.

The coefficient of linear expansion from 40° C. to 100° C. is 0·0000115 per ° C.; from 40° C to 700° C. it is 0·0000161.

The heat conductivity from 40° C. to 100° C. is 0·036 C.G.S. units, i.e. about 3·5 per cent that of copper.

In regard to its mechanical strength properties some representative
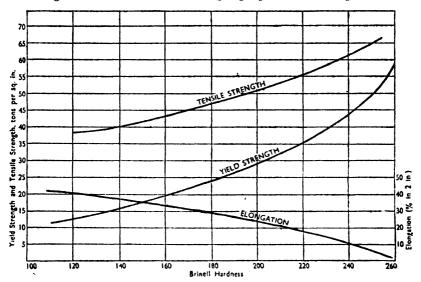
FIG. 106. AVERAGE TENSILE PROPERTIES OF HOT-ROLLED AND COLD-DRAWN INCONEL RODS

values are shown in Fig. 106 for hot-rolled and cold-drawn Incone rods.

The cast metal has a yield point of 18 tons per sq. in. and tensile strength of 32 tons per sq. in., with 10 to 15 per cent elongation. The Brinell hardness is about 160.

The modulus of elasticity in tension is 31×10^6 lb. per sq. in. and in torsion, $10·3 \times 10^6$ lb. per sq. in.

In regard to the fatigue strength the endurance limits of the hot-rolled and cold-drawn bar are 16 and 20 tons per sq. in. respectively. For the fully annealed metal the value is 14·5 tons per sq. in.

In common with other members of the nickel-chromium-iron group of alloys, Inconel has great strength and resistance to oxidation at elevated temperatures, as shown by the short-time test results given in Fig. 107.

Inconel is *annealed* after heavy cold-working by heating to 980° C

for 10 to 15 min. At 535° C. the internal stresses are relieved to some extent; at 760° C. they are fully relieved. The mode of cooling from these temperatures is unimportant; quenching or furnace cooling both produce proper softening. The alloy may be *bent or pressed* without
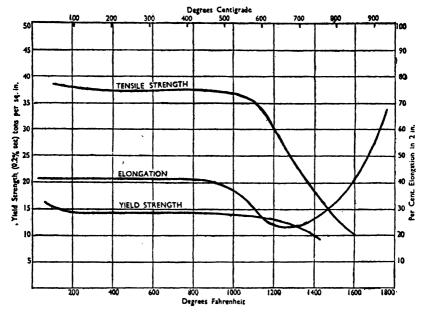
FIG. 107. SHORT-TIME HIGH-TEMPERATURE TENSILE PROPERTIES
OF INCONEL

difficulty, as it is quite ductile and does not work-harden very rapidly.

In *machining Inconel* a good deal of heat is usually developed, so that high-speed tools require careful heat-treatment and grinding. For ordinary lathe work low cutting speeds are necessary, namely, about 45 ft. per min. with $\frac{1}{8}$ in. cut and $\frac{1}{32}$ in. feed. The alloy machines uniformly and does not drag or tear with properly designed tools and sharp edges.

Inconel can be *soft soldered* with ordinary tinsmith's solder, using a neutral zinc chloride solution as a flux. It can be welded by the oxy-acetylene and metallic arc methods without difficulty, using special flux and feeding rods (or flux-coated filler rods) in the former method. In electric arc welding flux-coated electrodes are employed and the work is made negative.

Applications of Inconel

On account of its high mechanical strength properties and corrosion resistance at ordinary and elevated temperatures, Inconel has a wide range of engineering and industrial applications.

In engineering work it is employed for *springs* which are used under conditions of elevated temperature and exposure to corrosive action. The alloy is so ductile that it can be wrapped around its own diameter

FIG. 108. AIRCRAFT ENGINE EXHAUST MANIFOLD IN INCONEL
(Rolls Royce, Ltd.)

without fracture. Inconel springs are frequently used at temperatures of 400° C. For maximum resistance to fatigue or high temperature Inconel springs should be heated after forming for 2 hours at 375° C. to 400° C.

Inconel is also used for the *exhaust manifolds* of aircraft engines. A typical example of its employment is for the ejector-type manifolds of Rolls Royce "Merlin" engines; it is well suited for this purpose, being unaffected by the hot exhaust gases which readily attack ordinary steels.

Corrosion Resistance

Inconel has a very high resistance to corrosion and tarnishing by most acids and alkalis, and on this account is used for containers and fittings for food manufacture—particularly where dairy products and fruit juices are involved. The chromium content makes it superior to pure nickel for these purposes. However, the oxidizing effect of dissolved air alone is not sufficient to ensure complete passivity and freedom from attack by air-saturated mineral acids or concentrated

organic acids. The alloy, however, remains bright indefinitely in indoor atmospheres and is immune to corrosion in sulphurous outdoor atmospheres. Whilst highly resistant to moving salt water it may become pitted in quiet or stagnant salt water. It is unaffected by dry gases at atmospheric temperature, but is not resistant to wet chlorine, bromine or sulphur dioxide. It is completely resistant to mixtures of steam, air and carbon dioxide and is especially useful in contact with steam at temperatures in excess of 425° C.

Inconel resists progressive oxidation at temperatures up to 1100° C. and for this reason is employed for the sheathing of electric heating elements.

The Nickel Silvers

This group of alloys contains nickel, copper and zinc and may be regarded as nickel brasses. It includes alloys previously known as *German silvers*, although these do not contain any silver but are of silvery-white appearance.

The compositions of nickel-silver alloys cover a fairly wide range, namely; copper from 50 to 65 per cent; nickel from 7 to 30 per cent, and zinc from 10 to 25 per cent. In many of these alloys the chief purpose of the nickel is to produce a fine white colour whilst at the same time improving the mechanical properties, notably ductility and toughness; it also renders the metal more corrosion-resistant.

Table 74 shows the tensile strengths of a number of nickel-silver alloys, as tested in the form of rolled strip*—

TABLE 74

TENSILE PROPERTIES OF NICKEL-SILVER ALLOYS
(Tests on Strip)

Percentage Composition			Condition	Tensile Strength Tons per sq. in.	Elongation per cent
Ni	Cu	Zn			
30	47	23	Hard .	58·0	2
30	47	23	Annealed .	32·5	32
25	55	20	Annealed .	31·5	38
18	64	18	Hard .	42·0	2·5
18	64	18	Annealed .	26·0	33
18	55	27	Hard .	47·8	2
18	55	27	Annealed .	30·8	29
10	62	28	Hard .	41·0	4
10	62	28	Annealed .	28·0	48

* Bureau of Information on Nickel.

Nickel silvers may conveniently be grouped into two principal classes, namely, the *alpha* and the *alpha-beta* ones.

The *alpha alloys* are those containing copper and zinc in the approximate ratio of 70 to 30, with nickel varying from small percentages up to about 30 per cent. The most useful alloys are those of the higher nickel content. These alloys can be cold-worked, stamped and drawn with excellent results, but occasional annealing is necessary for deep drawing and pressing. The alpha nickel-silver alloys usually have heavy composition gradients in the cast state but such gradients are not got rid of entirely by working and annealing.

The annealing temperature is from 650° C. to 750° C.

The *alpha-beta nickel-silver alloys* have the characteristics of the alpha-beta of the copper-zinc system but modified by the presence of nickel. They possess good strength properties and actually constitute high tensile nickel brasses.

In regard to their fabrication, these alloys can be extruded, hot stamped and otherwise worked in a similar manner to alpha-beta brasses. A typical percentage composition is as follows: copper, 45; zinc, 45; and nickel, 10. The Brinell hardness of strip nickel silvers of 10 to 30 per cent nickel content range from about 75 to 90.

Concerning *the applications of nickel silvers*, these are used where a high-strength, ductile and corrosion-resisting alloy is required having a silvery-white colour; the latter is obtained with the higher nickel content.

The principal commercial uses of nickel silver are as castings for valves and other plumbing fittings, ornamental hardware, marine hardware, automobile fittings, typewriter parts, musical instruments, and as a foundation for spoons and forks, etc., which are afterwards silver-plated (E.P.N.S.). In the case of castings and other alloy parts that have to be machined it is the practice to add lead for this purpose. When thin section castings are required aluminium, in small quantities, is added, but the resulting castings have a tendency to minute porosity such that they will not withstand water pressure without leaking.

Some typical compositions of nickel silvers for specific purposes are given in Table 75.

Nickel Alloy for High Temperature Use

An alloy used in certain furnaces where firebricks are held together by means of bolts, and the excessive temperatures previously caused failure of these bolts under severe corrosive influences, is one containing 96 per cent of nickel and 4 per cent of manganese. This alloy, under

TABLE 75

NICKEL-SILVER ALLOYS

Alloy	Ni	Cu	Zn	Sn	Pb	Others
Hardware　.　.	18	50	32	---	—	Aluminium (as flux) 0·5
Valves and plumbing fittings　.　.	16·5	49·5	26	—	7·5	
	20	59	10	7	4	
Automobile fittings .	24	56	13·5	—	3	Aluminium 2, Iron up to 1·0
Ingot metal　.　.	12	59	29	—	—	
Brazing solder　.　.	8–20	35–40	40–55	—	—	

the conditions stated, becomes coated with a protective film of manganese oxide. It can be either cast or forged and a specimen bolt of the metal has been bent through 180° without fracture.

Nickel Coinage

Although not employed in this country this represents one of the oldest applications of nickel. The principal interesting development of recent times has been the substitution of pure nickel coinage for the older nickel-copper coinage started about 1850. Several countries, including Canada, have within the past few years adopted a pure nickel coinage, and are finding it better than the copper-nickel composition. It is hard, very resistant to wear, and gives a very clean coin. Because of its hardness and high melting point, it is difficult to counterfeit; in this connection a magnetic test can be used to detect spurious coins. In all, there are about seventy-five countries throughout the world using some type of nickel coinage.

Sparking Plug Electrodes

High nickel alloys have proved among the most suitable for aircraft and automobile sparking plug electrodes on account of their erosion resistance and low sparking voltages. Pure nickel is often used; or an alloy consisting of 97 per cent nickel and 3 per cent of manganese. Nickel-alloy electrodes have more recently been superseded by platinum-iridium alloy ones.

Nickel-barium Alloys for Sparking Plug Electrodes

When from 0·1 to 0·2 per cent of barium is added to nickel it has a somewhat similar effect upon the nickel as the same percentage of

carbon has on iron. The resulting alloy has a greater resistance to the action of hot corrosive gases than nickel, as indicated by the results given in Fig. 109.* The hardness and tensile strength are increased by the small barium content. Further, there is a marked increase in the thermionic electron emission from the alloy as compared with nickel, which is one of the properties that has led to its extensive use for sparking plug electrodes and also for wireless valves. The inclusion of 2 to 4 per cent of chromium in this alloy has also been found to increase the total emission from a given surface.

The 1·5 per cent nickel-barium alloys are ductile and are readily rolled or drawn into fine wire or ribbon, with a bright smooth nickel-coloured surface.

Nickel Plating Other Metals

Various common metals can be given a coating of nickel by the electro-plating method, as a protection against corrosion and for enhanced appearance purposes.
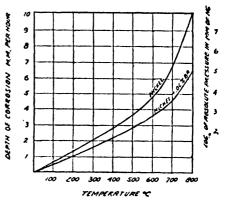
FIG. 109. CORROSION OF 0·06 PER CENT BARIUM NICKEL AND NICKEL IN SULPHUR DIOXIDE GAS

More recently, however, chromium plating has to a large extent replaced nickel plating for both purposes, but it is generally necessary to employ nickel undercoatings; thus, practically all automobile parts are nickel plated prior to chromium plating. The nickel layer then inhibits corrosion and at the same time affords a satisfactory key to the base metal. It should be mentioned that for decorative purposes the layer of chromium is extremely thin, i.e. of the order of 0·00002 in., and all metals when so deposited are porous. The pores therefore give access to the corrosive media and allow them to attack the base metal unless it is fully protected. This can be effected with entire satisfaction by using a relatively thick underlay of nickel. In regard to the adhesion of nickel to the base metal, by careful attention to the initial cleaning, removal of grease, etc., followed by anodic etching, it is possible to obtain adhesion values of 30 tons per sq. in. and over when nickel is electro-deposited on steel. Corresponding high adhesion values are obtained for other base metals.

* "Alloys of Barium and Nickel," D. W. Randolph, *Metal Industry*, 16th November, 1934.

Articles for indoor use are given a coating of nickel about 0·0005 in. thick, and this coating is covered by one of chromium 0·00002 in. thick. For outdoor use the nickel and chromium coatings are 0·001 in. and 0·00002 in. thick respectively.

The physical properties of the nickel now used for plating are similar to those of the pure rolled nickel (malleable grade).

Bright Nickel Plating

The more recent developments include those of fast-plating, automatic machinery and the employment of bright nickel plating; the adoption of the latter process reduces the buffing costs by as much as 25 per cent.

Briefly, the bright plating method depends upon the existence of an initially bright surface on the metal to be plated and the inclusion of organic compounds which encourage brightness by colloidal action, preventing the growth of large crystals of nickel and limiting the grain size to less than one-thousandth of a millimetre. A sulphate solution containing nickel and cobalt is employed, roughly in the proportion of ten of the former to one of the latter. The colloidal brightening agents are formaldehyde and sodium formate. The solution works hot and current densities up to 100 amperes per sq. ft. of cathode surface have been attained, using 15 per cent cobalt-nickel anodes. The *pH* figure is elastic, ranging from about 3 to 4·5. Deposits of any thickness can be built up and still remain bright and ductile, due to the presence of the co-deposited cobalt, present to about 10 per cent by weight of the deposit.

Several interesting features about the deposit make it an ideal undercoat for chromium plating. The alloy does not become passified or etched by chromic acid, thus increasing the potential covering power of the chromium. Previously this phenomenon of passivity had been the cause of indifferent throwing power and of stripped deposits on "straight" nickel. The electrical conductivity of the new alloy is greater than deposited nickel, and the presence of the cobalt ensures a much longer life against corrosion.

An important phase of this process is the preliminary cleaning of the surface before the nickel is deposited. The cleaning methods have been so improved that it is feasible to deposit nickel directly on the base metal. Copper is often used as a base for nickel in several applications, one of which is *the nickel plating of zinc alloy die-castings.*

CHAPTER VII

BEARING METALS AND OTHER MATERIALS

THERE is now a wide range of alloys employed for the bearings of machines, engines, and the shafts of rotating parts in general, as well as for sliding members, such as piston rods and crossheads.

The selection of the particular type of bearing metal depends upon the conditions under which it is to be used and involves factors relating to bearing pressures, rubbing speeds, temperatures, impact or pounding effects, lubrication, etc.

In the present considerations the bearing materials for rotating shafts of machinery and engines are given the more prominent attention, and particular reference is made to the bearing requirements of automobile and aircraft engines.

Before passing on to the actual subject of bearing metals and certain other materials of a non-metallic nature, it may be of interest to consider in brief the desirable qualities of such bearing materials from the point of view of selecting the most suitable one for a particular purpose.

Some General Considerations

The desirable properties of a satisfactory bearing material may be summarized as follows: (1) Low coefficient of friction; (2) good wearing qualities; (3) ability to withstand continuously the bearing pressures, whether of a steady or variable nature; in particular impact or pounding action; (4) ability to operate satisfactorily with suitable lubrication means at the maximum rubbing speeds to which it will be subjected in practice; (5) sufficiently high melting point; (6) high thermal conductivity; (7) good casting qualities; (8) the desired degree of plasticity under load for its particular application; (9) minimum shrinkage after casting; (10) non-corrosive properties; (11) economical in cost and quantity employed.

Coefficient of Friction. In order to avoid waste of energy in power transmission, the frictional loss must be kept down to a minimum. Since this loss is dependent upon the value of the coefficient of friction between the lubricated shaft and its bearing, it is necessary to keep the coefficient value down to a minimum. In this connection the coefficients of friction of journal bearings usually lie between the limits of 0·0015 and 0·02 under working conditions of loading, speed and lubrication.

The effects of inadequate lubrication, as when starting engines from cold or under conditions of temporary overheating, must be provided for in most bearings and the influence of these factors on the frictional coefficient determined.

A knowledge of the bearing friction also involves the viscosity of the lubricating oil, angular velocity of the shaft or bearing and the bearing pressure. Thus the coefficient friction of a lubricated bearing is given by the following relation—

$$\mu = 3\cdot8\sqrt{\frac{\eta w}{p}}$$

where η = oil viscosity, w = angular velocity, p = load per unit projected area of bearing = total load ÷ length × diameter of bearing.

It will be observed that the coefficient μ increases with the viscosity and angular velocity, but diminishes with increase of pressure—owing to the reduction in thickness of the oil film.

FIG. 110. RELATION BETWEEN FRICTIONAL COEFFICIENT AND RUBBING SPEED

The formula stated, whilst applicable to normal running conditions, does not hold for starting or low rubbing speeds. In this connection the results of tests by Gümbel and Stribeck, reproduced in Fig. 110,* show that the dry frictional coefficient at A is considerably higher than the normal value at D, falling progressively as the speed increases. If the fluid friction at D persisted until the speed fell to zero the curve would follow the dotted line. As the oil becomes thinner, however, the point of inflexion C is reached where the first contact between the high spots on the bearing and shaft occurs. With further decrease of speed dry friction occurs to an increasing extent and below B exceeds the fluid friction, thereafter increasing until at zero velocity it reaches the normal dry friction value A for the metals of the shaft and journal. Actually, there is always a small amount of lubricant on the surfaces, and the zero frictional coefficients in practice correspond to what is known as "boundary" lubrication conditions when they are appreciably less than for the dry condition. Such boundary conditions are liable to occur in petrol engines between the pistons and cylinder walls.†

Resistance to Wear. A bearing material must be sufficiently hard to

* "Lead Bronze Bearings," C.D.A. Publication No. 33.
† *Aircraft Engines*, Chapter VIII, Vol. II, A. W. Judge (Chapman & Hall, Ltd.).

give long wearing qualities, but must not be hard enough to cause wear of the shaft. This condition leads to the conclusion that the selection of a bearing metal is governed to some extent by the metal used for the shaft and its physical condition. Thus for unhardened steel shafts the softer lead-containing bearing metals are applicable, whereas for a case-hardened or nitrided steel shaft the harder high-tin content phosphor-bronze or other copper alloy bearing metals would be employed.

The bearing metals belonging to the tin-base and lead-base classes are generally considered as providing *two major constituents*, namely,

a softer plastic matrix containing a relatively large number of hard grains or particles embedded in it. The hard particles resist the wear and abrasion of the shaft whilst the softer matrix allows the bearing to accommodate itself to the shape of and load on the shaft and also on account of its deformation—by plastic flow—to accommodate itself to a certain degree of non-align-ment between the shaft and its bearing.

Fig. 111 illustrates the general kind of structure of an ordinary whitemetal, with the harder antimony-tin cubical
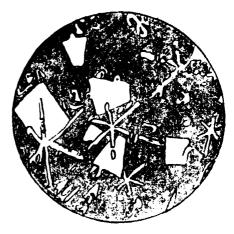
FIG. 111. STRUCTURE OF WHITEMETAL

crystals or copper-tin needles in relief, shown against the softer plastic matrix consisting of a eutectic of the metals.

Bearing metals of this class are definitely better than any single homogeneous metal or alloy since, if hard enough to give satisfactory wearing qualities and a low coefficient of friction, it is not sufficiently plastic to take account of imperfect alignment, so that the load is supported on a few local areas and eventually the oil film may break down and possibly cause seizure and scoring of the journal.

Bearing Pressures. The bearing material must possess sufficient compressive strength at its normal running temperature to withstand the bearing pressures without fracture or appreciable distortion, e.g. end flow. It must, however, not have an excessive strength since a certain degree of plasticity is generally desirable for the reasons previously stated. The exception to this rule is that of hard bearing

materials, such as the bearing bronzes which are employed for accurately aligned bearings.

The bearing pressure is usually expressed as the total load on the bearing divided by the projected area, i.e. the length × diameter.

The bearing pressures in engineering practice range from the lower values of 100 to 500 lb. per sq. in. for heavy loads and low shaft speeds in cases where the lubricating film cannot be maintained, up to the higher values of 1000 to 3000 lb. per sq. in. for pressure-lubricated high-speed bearings of aircraft and automobile engines.

In the case of *line shafting* and *machine tool bearings* which may have to operate under sparse or uncertain conditions of lubrication, the bearing pressures are kept low to obviate mechanical failure and limit the temperature rise of the bearing. In such applications for steel and bronze combinations the bearing pressures seldom exceed 300 lb. per sq. in.

Since the rubbing speed is also concerned in any considerations of bearing design, it is usual to regard the product of the rubbing speed (in feet per min.) and the maximum bearing pressure (in lb. per sq. in.), *known as the PV factor*, as an indication of the loading on any particular class of bearing. Although this factor is not always a good indication, if the bearing is designed on sound lines with a proper knowledge of lubrication requirements it affords a useful method of assessing the value of a bearing material in any particular application. It must, however, be remembered that viscous drag on the oil film builds up oil pressure in well-designed bearings so that high loads may be carried at high speeds—a condition that does not exist in heavily loaded low-speed bearings.

Aircraft and Automobile Bearing Pressures. In regard to the bearing pressures employed in modern aircraft and automobile engines, values up to 1500 lb. per sq. in. have been used for high grade tin-base white-metals with corresponding *PV* values up to 40,000 ft.-lb.-min.-sq. in.

For lead-bronze bearings values up to 2800 lb. per sq. in. in the case of high-speed C.1 engines have been satisfactorily employed; the bearings in this case were steel-backed ones with copper-lead bearing metal. The corresponding *PV* values are 65,000 to 75,000.
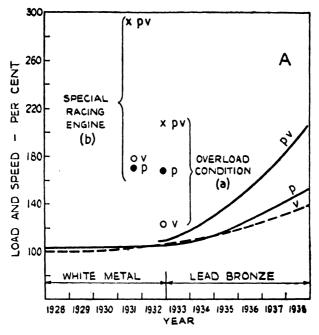
Copper-silver alloy bearings have been used in America under loads of 2000 lb. per sq. in. and *PV* values up to 70,000.

The progress made in connection with aircraft engine big-end and main crankshaft journal bearings over a ten-year period is illustrated in Fig. 112.* The standard production engines will run satisfactorily

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* "Materials of Aircraft Construction," H. J. Gough, *Journ. Roy. Aeron. Soc.*, 26th May, 1938.

under overload conditions for a limited life; the points marked (a) in Fig. 112 relate to such a test, whilst those marked (b) refer to a racing engine of 5½ hours' useful life.

Melting Point. The melting point of the bearing metal must not be too low, since accidental momentary heating of the bearing due

FIG. 112. ILLUSTRATING PROGRESS IN AIRCRAFT BIG-END CONNECTING
ROD BEARINGS OVER A TEN-YEAR PERIOD

to operating conditions will cause a serious loss of strength properties and may result in the plasticity becoming sufficient to cause the metal to flow sideways from the bearing so that ultimate seizure may occur. If too high, casting difficulties are likely to be met with.

Permanent Plasticity. The plasticity of the bearing metal should not be affected by working pressures and temperatures, and the alloy used must not work-harden under its bearing loads and impacts; otherwise it is likely to lose its initial plasticity and will not yield in the areas of greatest local loading pressure. Some of the whitemetals possess the desirable property of continuous self-annealing at their

working temperatures, when these are well below the melting points, so that the plasticity is of a fairly permanent nature.

Thermal Conductivity. The heat developed in a bearing should be readily conducted away through the bearing metal to its housing, thus keeping the bearing metal as cool as possible. Those alloys with the higher thermal conductivities, e.g. the copper ones, are advantageous in this respect.

Temperature Effects. In the case of bearings used in automobile and aircraft engines the high pressure lubricating oil is passed through the main and big-end bearings at a sufficiently high rate to prevent the temperature of the bearing metal from exceeding about 70° to 90° C. The strength properties of the high-tin content and lead-bronze alloys are generally ample under these conditions, but in instances where bearings may exceed these temperatures a serious loss of strength and hardness is liable to occur.

The effect of elevated temperature upon the strength property of a high-tin whitemetal having the following percentage composition is shown by the results given in Table 76: * Sn, 92·3; Sb, 3·78; Cu, 3·55; Pb, 0·30. The casting temperature was 450° C. and mould temperature 20° C.

TABLE 76

STRENGTH OF WHITEMETAL AT ELEVATED TEMPERATURES

Test Temperature, °C.	Maximum Stress Tons per sq. in.	Yield Point, Tons per sq. in.	Elongation, per cent on 4 $\sqrt{A}$	Reduction in Area per cent
18	4·25	3·4	20·5	24
50	3·6	2·85	26	34
100	2·38	1·95	25	35
150	1·7	1·16	32	38
175	1·2	0·7	36	41

It will be observed that the tensile strength and yield point fall to a notable extent as the temperature is increased, so that at the boiling point of water the strength is a little over one-half that at normal air temperature. The ductility and plasticity increase as the temperature is increased, as shown by the elongation and reduction in area values.

* "Whitemetal Bearing Alloys at Elevated Temperatures," H. Greenwood Tech. Publn. Internat. Tin Research and Devel. Council, August, 1937.

In regard to the effect of temperature upon the hardness of bearing metals this is even more marked in the case of the tin-base and lead-base alloys, but to a considerably less extent in the high-performance alloys such as the lead-bronzes, aluminium-base and cadmium-base alloys. The latter bearing metals have from two to three times the hardnesses of the whitemetals at air temperatures, and even at temperatures as high as 200° C. the aluminium-base and lead-bronzes usually have higher hardness values than those of the tin-base alloys at air temperature.

The compositions and hardnesses at temperatures of 20° C., 100° C. and 200° C. of some typical bearing metals, including the more recent high-performance ones employed on aircraft and automobile engines, are given in Table 77.

Fatigue Cracking. Many of the tin-base bearing alloys, known as whitemetals, when employed under severe conditions of service, notably excessive loadings or impacts, fail by a process known as fatigue cracking. The usual indication of the commencement of this mode of failure is the appearance on the surface of a series of fine cracks forming a kind of network. Afterwards the cracks spread inwards and also sideways until finally they extend right through the metal and then small pieces break away eventually causing failure of the bearing; this mode of failure was experienced in the early days of the high-speed C.I. engine, owing to the severe loads and load variations during the working cycles. This type of failure is associated with the fatigue range of the metal and is influenced by the existence of tensile stresses which act so as to reduce the fatigue range and thus cause eventual failure. Those bearing metals with the higher fatigue limits are therefore more suitable for application in conditions causing failure in whitemetals of the type described. In this connection the modern lead-bronze alloys are markedly superior to the best whitemetals.

The addition of cadmium to certain whitemetal compositions has been shown to increase their fatigue range; thus, 1 per cent of cadmium added to a tin-base alloy will raise the fatigue limit by about 0·4 ton per sq. in.

A useful indication of the condition of tin-base alloys can be obtained by etching test bearings after service so as to show up the grain structure. The presence of large and non-uniform grain structure and cracks along the grain boundaries reveals the initial conditions associated with ultimate failure. On the other hand absence of such failure conditions is indicated by a fine uniform grain structure.

Adhesion to Bearing Shell. In the majority of instances, the

TABLE 77

COMPOSITIONS AND HARDNESSES OF BEARING METALS

Group	Composition, per cent									Brinell Hardness		
	Sn	Pb	Cu	Sb	As	Fe	Ni	Cd	Misc.	20°	100°	200°
Tin-base whitemetals	92·9	—	3·4	3·6	—	0·05	0·05	—		13	6	2·5
	87·2	0·2	5·7	6·85	0·02	0·03	—	—		22	8	3
	80·4	0·7	7·4	11·4	0·02	0·04	—	—		27	10	3
Lead-base whitemetal	10·7	70·4	1·7	15·15	0·15	0·06	0·01	1·83		22	9	4
Cadmium-base bearing metals	—	—	1·9	—	—	—	—	97·6		38	19	6
	—	—	—	—	—	—	3·1	96·42	0·48 Ag	35	16	5·5
Aluminium-base bearing metals	Al with additions principally of metals of the iron group. Composition not specified.									42	40	30
										49	45	33
Lead bronzes	—	30	70	—	—	—	—	—	Nominal composition	30	23	17·5
	2	28	70	—	—	—	—	—		45	41	38

whitemetals and lead bronzes are used as linings to steel or bronze shells. It is essential, therefore, that the bond between the bearing metal and its shell should be as strong as possible. In this respect certain alloys used for bearing purposes are much better than others. The high-tin content whitemetals will adhere to their bearing shells and to steel connecting rod big-ends if the metal of the latter is thoroughly cleaned and tinned beforehand. Again, the cadmium-rich bearing metals are found to adhere strongly to steel shells.

Alloys which show excessive shrinkage during solidification are unsatisfactory for use with bearing shells since it is very difficult to obtain proper bonding of the two metals, and any appreciable temperature increase in service tends to separate them.

Metals for Bearings

The various desirable properties of a bearing are in general dependent upon (1) the chemical composition of the alloy used, and (2) the microstructure or arrangement of the constituents; the latter property is to a large extent governed by the casting methods used in making the bearing.

The principal metals employed for various classes of bearings used in engineering applications include tin, lead, copper, antimony, zinc, nickel, silver, and cadmium.

The more widely used bearing metals may conveniently be grouped into four principal classes, namely, as follows: (1) *Tin-base Alloys*; (2) *Lead-base Alloys*; (3) *Copper-base Alloys*; (4) *Special alloys* for specific applications, e.g. high-duty purposes.

Tin-base Alloys

These bearing metals include those containing the greater proportion of tin, with copper and antimony, and are known as the *Whitemetals*; they include the well-known Babbitt metal,* having approximately the following composition: Tin, 83·33; antimony, 8·33; copper, 8·33 per cent.

When small proportions of copper, exceeding 1 per cent, are added to tin the resulting alloy has a microstructure consisting of needle-like crystals of a copper-tin compound having about 60 per cent of tin, embedded in a matrix consisting of a eutectic mixture of tin with a small amount of copper-tin compound; the latter is designated by the letter ε in the equilibrium diagram (Fig. 113).†

If, on the other hand, antimony is added to tin then if the amount

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* First introduced by Sir Isaac Babbitt in 1839.

† C. T. Heycock and F. H. Neville (*Phil. Trans. Roy. Soc.*, 1903, 202, 1).

is below 7 per cent a solid solution only is obtained. When more than 7 per cent of antimony is present the resultant alloy consists of cubic crystals of antimony-tin in the solid solution.

Each of the two binary alloys of tin, with copper and lead respectively, consists of harder constituents in a softer matrix, but unfor-
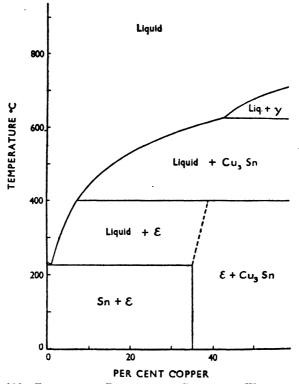
FIG. 113. EQUILIBRIUM DIAGRAM FOR COPPER-TIN WHITEMETALS

tunately neither alloy is entirely satisfactory as a bearing metal, so that it is necessary *to include both copper and antimony in the tin* in order to obtain the desired bearing metal properties.

When less than 7 per cent of antimony, with 2 to 4 per cent of copper, is present in the tin, the alloy obtained consists of a softer matrix in which needle-like crystals of the copper-tin compound are embedded; the matrix consists of a mixture of this compound with antimony-tin solid solution together with some tin.

A typical bearing metal* of this class contains 3·5 per cent each

* "Bearing Metals," W. T. Griffiths, *Proc. Inst. Marine Engrs.*, 1925–6.

of copper and antimony with the rest of tin. It has a tensile strength
of just over 5 tons per sq. in., with 11·5 per cent elongation (on 2 in.)
and a Brinell hardness of 25. In compression the yield point is 3·6
tons per sq. in., and it requires a compressive stress of 14·7 tons per
sq. in. to compress a specimen to one-half of its length.

If the percentages of copper or antimony are increased above 3·5
and 7·0 respectively, the hardness of the metal is increased, but
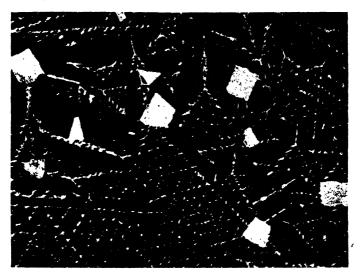
FIG. 114. STRUCTURE OF TIN-ANTIMONY-COPPER ALLOY. × 100

owing to the brittleness of the crystal constituents there is also greater
brittleness in the resulting alloy. For this reason the antimony is
usually kept down below 10 or 12 per cent.

Another type of alloy is obtained if more than 7 per cent of anti-
mony is employed when the cubic crystals of antimony-tin compound
are obtained. In the binary alloy of antimony and tin these crystals
begin to separate first from the molten alloy and, being lighter, collect
near the surface. In the ternary alloy, however, the needle-like crystals
of copper-tin are the first to solidify and these prevent the cubic
antimony-tin crystals from moving to the surface, so that a more
uniform distribution throughout the matrix is therefore obtained.
Fig. 114 illustrates the microstructure of a typical ternary tin-base
alloy consisting of 87 per cent tin, 9 per cent antimony, and 4 per cent
copper. It shows the cubes of tin-antimony and needle-crystals of
copper-tin embedded in the softer matrix consisting largely of tin.

An alloy consisting of 10·5 per cent antimony, 3·5 per cent copper, and the rest tin has a tensile strength of 6·6 tons per sq. in., elongation of 7·1 per cent, with Brinell hardness of 33·3, and compressive yield point of 4·3. It requires a compressive stress of 17·2 tons per sq. in. to reduce its length to one-half.

An alloy containing 11 per cent each of copper and antimony, with the rest tin, belongs to the so-called *"plastic metals."* The effect of the higher copper content is to extend the temperature range between the first separation of the crystals and complete solidification. During this stage the metal, which is then a mixture of solid and liquid, is in a pasty condition, and can be moulded to any desired shape; it is therefore useful for bearing repair purposes.

The high tin content whitemetals of the class considered have wide applications for engineering bearings, in conjunction with steel or bronze shells or journals, but on account of the high proportion of tin are relatively expensive.

Effect of Lead in Whitemetals. In order to reduce the expense, *lead is often added* to the ternary alloys previously mentioned. Since lead does not form any compounds or solid solutions with the tin, it is present in the resulting alloy either as fine globules of lead or as part of the intimate eutectic mixture comprising the matrix.

The general effect of lead additions to high tin whitemetals is to reduce the hardness and result in an almost complete loss of elongation. It is also claimed to reduce the frictional coefficient.

A typical alloy of this class has the following percentage composition: Sn, 80·0; Sb, 11·0; Cu, 3·0; Pb, 6·0. The tensile strength is 5·7 tons per sq. in., with zero elongation and a Brinell hardness of 32. The yield point in compression is 4·6 tons per sq. in., and the compressive stress necessary to reduce the test specimen to one-half its length is 17·5 tons per sq. in.

Thin Whitemetal Linings. Normally, in the case of whitemetal-lined steel shell bearings the thickness of the whitemetal is from 0·030 to 0·050 in., the shell thickness being from 0·050 to 0·075 in. As the bearing itself is subjected to a bending effect the whitemetal is in compression and tension alternately, with the maximum stress value at the surface. The neutral axis of bending is then situated in the steel portion. Thus the whitemetal experiences the whole range of stress reversals due to reversed bending.

. In more recent shell-type bearings for main and big-ends of connecting rods of automobile engines it has become the practice to reduce the thickness of the whitemetal to 0·002 to 0·004 in., and although the maximum surface stress remains the same, the steel backing takes

most of the other stress. The supporting shell enables the local high stresses in the whitemetal to be redistributed to itself. If a thin lining of this type should fail through lack of lubrication and run, there will still be only a small amount of clearance between the shaft and steel shell, so that the engine could continue to operate for a further but limited period, if suitable lubrication were provided.

The tri-fabricated bearings mentioned on page 246 have an advantage in this respect, namely, that in the event of the whitemetal running out the lead bronze provides a good bearing metal for the steel shaft.

Lead-base Bearing Metals

The lead-base alloys used for bearing purposes contain lead in place of tin, together with between 10 and 15 per cent of antimony, up to about 1·5 per cent of copper, and up to about 20 per cent of tin, although the usual percentages of tin lie between 2 and 10.

Without the tin content these alloys consist of cubic crystals of antimony in a matrix of antimony-lead eutectic. The presence of tin results in the replacement of the cubic crystals of antimony by the less brittle cubic ones of a solid solution of an antimony-tin compound in tin.

The lead-base alloys are cheaper than the tin-base ones, but are not as strong and do not possess the load-carrying capacity, so that they are generally employed for lightly-loaded bearings; moreover, their strength falls more rapidly with temperature increase than the tin-base alloys. The lead-base alloys are softer and more easily deformed. Further, more care is necessary in casting them owing to their higher (molten) viscosity. These bearing alloys are generally claimed to have lower frictional coefficients than the tin-base ones and rather better wearing qualities.

In the case of the binary lead-antimony alloys the frictional coefficient is relatively quite low and the alloys containing up to about 20 per cent of antimony have good casting properties with little shrinkage. The hardness of the lead is increased from its normal value of 4 on the Brinell scale progressively, up to about 21, with increasing proportions of antimony up to 20 per cent. The addition of tin increases the hardness as shown by the values given in Table 78.

With the addition of antimony the melting point falls from that of pure lead, namely, 327° C. to about 230° C. for the 12 per cent antimony-lead (eutectic) and then increases according to a linear law up to 630° C. for the pure antimony.

*A more recent lead-base alloy** used in the United States and claimed

* *Automotive Industries*, 15th July, 1941.

TABLE 78

HARDNESS PROPERTIES OF LEAD-TIN-ANTIMONY ALLOYS

Composition, per cent			Brinell Hardness	Remarks
Lead	Tin	Antimony		
90	5	5	15·2	
85	10	5	15·1	
80	15	5	16·7	
75	20	5	18·0	
70	25	5	16·8	
65	30	5	15·1	
85	5	10	23·2	Tensile strength a maximum, being over 6 tons per square inch.
80	10	10	25·4	
75	15	10	26·4	Ductility a maximum for the series.
70	20	10	23·2	
65	25	10	24·0	
80	5	15	25·6	
75	10	15	31·0	
70	15	15	32·0	
65	20	15	27·6	
75	5	20	26·7	High tensile strength, but brittle series.
70	10	20	·37·0	
65	15	20	35·6	Bearings liable to crack in service.
70	5	25	27·8	
65	10	25	33·6	
65	5	30	28·8	

to be equal to commercial tin-base alloys in all its physical properties contains 12·5 per cent antimony, 0·75 per cent tin and the rest lead. The additions of small amounts of copper, bismuth, cadmium, nickel and mercury cause no appreciable alteration in the desirable properties so that it was concluded that the alloy was insensitive to impurities of the usual small amounts.

The alloy has a fine granular structure and low coefficient of friction. The cast alloy had a Brinell hardness of 22. After heating for 46 days at 150° C. and cooling, this value fell to 19·5. The hardness value at 150° C. was 10.

The cast alloy had tensile strengths at 25° C., 100° C. and 200° C. of 4·47, 3·00 and 0·85 tons per sq. in. respectively.

Tests made on the composition stability indicated that this was very satisfactory, and its rate of dross formation relatively low. The alloy is stated to have a relatively high fatigue strength.

Alkaline Earth Metal Additions. Attempts have been made to

TABLE 79

TYPICAL TIN AND LEAD-BASE BEARING ALLOYS

Name	Composition, per cent					Remarks
	Tin	Copper	Lead	Anti-mony	Bis-muth	
Babbitt No. 1 .	83·33	8·33	—	8·33	—	For high-speed high-pressure bearings, e.g. automobile engines.
,, No. 2 .	89	4	—	7	—	
,, No. 3 .	50	2	33	15	—	For medium pressures and speeds.
,, No. 4 .	5	—	80	15	—	For medium pressures and low speeds.
,, No. 5 .	—	—	90	10	—	For low pressures and speeds such as line shaftings.
Admiralty whitemetal	86	5·5	—	8·5	—	For high and medium pressure marine engine bearings.
Fry's whitemetal (typical)	86	3·5	—	10·5	—	Tensile strength 6·65 tons per sq. in. For automobile main and big-end bearings.
Locomotive white-metals	10–12	—	70–80	8–20	—	For eccentric straps, piston rod packings, etc.
Locomotive bearing metal	33	22	- -	45	—	For journal bearings.
Dynamo .	88	3·5	—	8	0·5	For high-speed dynamo bearings.
Plastic metal .	80	8	10	1	—	For bearing repairs and plastic moulding.
Universal bearing metal	6	—	77·25	16	0·25	Inexpensive general purpose bearing metal for light to medium loads and speeds.
Underwater whitemetal }	70	1–2	—	—	Zn 28–29	Used for underwater purposes, water-lubricated, e.g. stern tubes.
High-duty metal .	83	8·5	—	8·5	—	For lining thin shell automobile bearings. Melting point, 240° C.
Automobile bearing .	89	4	—	7	—	For high-speed high-load big-end and main bearings.
A.S.T.M. bearing metal 1	91	4·5	—	4·5	—	For crank-pin bearings of steam and I.C. engines; for lining shells; most plastic of tin-base alloys.
A.S.T.M. bearing metal 4	75	3	10	12	—	Engine main bearings and general machinery, machine tools, etc. For high pressures and medium speeds. Economical tin-base alloy.
A.S.T.M. bearing metal 7	10	—	75	15	—	Most economical of lead-base alloys. Very serviceable for general purposes. Replaces high-tin Babbitts for certain purposes.
A.S.T.M. bearing metal 11	—	—	85	15	—	Cheapest of bearing metals. Suitable for line shafting and use with softer steel shafts.

improve the strength properties of lead-base alloys by the addition of alkaline earth metals such as those of barium, calcium, sodium and lithium. They are more difficult to cast but possess good compressive stress and hardness properties, but are not as strong as high tin content whitemetals; moreover they are subject to excessive loss of hardening constituents on remelting.

A typical alloy of this class is the German *Bahnmetal*, having the following percentage composition: Pb, 98·66; Ca, 0·7; Na, 0·6; Li, 0·04. The microstructure consists of hard intermetallic compounds of lead with sodium and calcium, in a matrix of almost pure lead. The Brinell hardness is about 35. Other lead-alkali bearing metals include those known as *Frary*, *Satco*, *Lurgi* and *Can*.

Bahnmetal does not lose its hardness with rising temperature at the same rate as the tin-base and lead-base alloys and it possesses good anti-friction qualities. Tests made at the N.P.L. on Bahnmetal showed that it was unsuited to loads above 900 lb. per sq. in. whereas *a tin-base alloy* having 82 per cent tin, 10·9 per cent antimony, 3·8 per cent copper and 3·1 per cent lead ran satisfactorily under the same conditions of speed and lubrication up to a loading of 2,500 lb. per sq. in.

Zinc-base Alloys

Zinc has been used for the less expensive bearing metals in place of tin, and in some respects these alloys resemble the bronzes in which zinc is added to provide sounder castings. The zinc, however, goes into solution in the copper-tin solution, increasing the hardness but reducing the strength properties; it also raises the value of the frictional coefficient. A typical zinc-base alloy used in Germany during the last war, when tin was scarce, had the following percentage composition limits: Zn, 87–97; Cu, 2–10; Al, 1–6; Pb, 0–4.

These bearing alloys possess practically no ductility, and owing to the difficulty in bonding with steel or bronze bearing shells it is necessary to make the complete bearing block of the alloy. The coefficient of friction is about three times as great as for tin-base whitemetal and the bearing pressure limit is about 350 lb. per sq. in.; under these conditions these zinc-base alloys appear to be suitable only for lightly loaded bearings under adequate lubrication conditions.

Copper-base Alloys

This important group of bearing metals includes the bronzes (copper-tin alloys with or without small proportions of phosphorus, nickel, lead, zinc, etc.); the bearing brasses (copper-zinc alloys with

or without small additions of other elements); the copper-lead alloys known as lead bronzes; the aluminium and silicon bronzes.

In general the copper-base alloys are very much harder and stronger than the whitemetals previously described. They will withstand heavy bearing pressures and pounding action without distortion but, on account of their lack of plasticity, must be employed in accurate alignment in respect of the journals. Further, owing to their hardness they cannot be used satisfactorily with unhardened steel shafts, except in special cases where high pressure lubrication is maintained continuously. The bronzes and brasses employed for bearing purposes have higher coefficients of friction than the whitemetals. Unlike the latter, however, these harder bearing metals cannot be cast into shells or journals, and are therefore used "solid" as bushes, finished half-brasses or complete bearings. It may be mentioned that successful use has been made of rolled bronze strip of about $\frac{1}{16}$ to $\frac{1}{8}$ in. thickness for bearing shells inserted into the usual bearing housings of various other metals including cast iron and cast brass. The strip is rolled to cylindrical form and after insertion is given a final reaming operation; such bearings are employed for light-duty applications.

In other instances, namely, those of levers, forked ends and brackets having bearing holes, instead of using steel for these parts with inserted brass or bronze bushings, the complete units are made from hot stampings in a suitable brass or bronze.

As most of the bearing brasses and bronzes used in engineering practice have already been dealt with in Chapter V, it will be unnecessary to consider them further in this chapter, other than to give a summary (Table 80) of some typical bearing bronzes, together with their average compositions and mechanical properties and applications.

In regard to the *weights of the bearing bronzes*, the specific gravities vary from about 8·3 to 8·9, the leadbearing bronzes having the higher values.

The *thermal and electrical conductivities* of most bearing bronzes are of the order of 10 to 20 per cent of the corresponding high conductivity (H.C.) copper values according to composition. In the case of copper-lead bearing alloys, free from the addition of tin and phosphorus, much higher conductivities, namely, of the order of 50 per cent, are obtained.

Lead Bronze Bearing Metals

An important class of high-duty bearing alloys now employed for the bearings of automobile, compression-ignition and aircraft engines —and to which reference has previously been made—is that known

TABLE 80

SOME TYPICAL BEARING BRONZES

Nominal Percentage Composition by Weight				Average Mechanical Properties			Description and Applications
Copper	Tin	Lead	Zinc	Tensile Strength Tons per sq. in.	Elongation per cent on 2 in.	Brinell Hardness	
85	15			14	2	100	Hard wearing bronze suitable for heavy compressive loads. Employed for locomotive slide valves, bearings for turntables, etc.
89	10 min.			18	4	100	PHOSPHOR BRONZE suitable for heavy loading, and very widely employed.
88	10		2	17	20	65	ADMIRALTY GUNMETAL. A bronze for general casting purposes, especially to resist marine corrosion. Suitable for bearings when lubrication is good.
80	10	10		15	15	65	LEAD BRONZES possess good anti-friction properties combined with plasticity. May be applied where lubrication is doubtful.
77	8	15		14	15	60	Suitable for use where lubrication or alignment is still less satisfactory than for the above.
85	5	5	5	13	16	55	An alloy suitable for general castings, such as hydraulic fittings not requiring high strength. Only occasionally used for bearings but suitable for bearing shells.
74	1·2 max.	25		8	15	30	This alloy has high thermal conductivity and is capable of carrying higher loads at high speeds than "white-metals," and is therefore used for high-duty aeroplane and other engine crankshaft bearings, etc. Special technique in casting is required.

[Copper Development Association]

as the *lead bronzes*, consisting of high copper content with lead and sometimes tin, nickel, zinc or iron. These bronzes may conveniently be classified* as follows—

(*a*) Binary copper-lead alloys with lead content of 10 to 20, 20 to 30 and over 30 per cent.

(*b*) Similar alloys but with the addition of other elements up to about 2 per cent, namely, nickel, tin or iron.

(*c*) Three groups of lead-tin bronzes with 4 to 22 per cent lead and 5 to 11 per cent tin.

* *Ante*, page 226, note (upper reference).

(d) Complex alloys with lead contents of 10 to 20 per cent and 20 to 35 per cent, with larger additions of tin, nickel, zinc, manganese and other elements.

The lead bronzes containing 70 to 75 per cent copper and about 30 to 25 per cent lead with tin up to about 1½ per cent (max.) are used for lining steel bearing shells for high-speed petrol and C.I. engines. They are not only much harder at all working temperatures than the best whitemetals, but have high wear resistance and high thermal conductivities; the latter property permits the rapid removal of heat from the bearings. Another advantageous factor is the low coefficient of friction, namely, about 0·002 (lubricated value).

The bearing pressures that may be employed with this type of lead bronze bearing are from 20 to 25 per cent higher than for the best whitemetals; for this reason they have been widely used for aircraft and high-speed C.I. engines.

As mentioned previously, the lead bronzes retain a much higher proportion of their room temperature strength at elevated temperatures (up to about 200° C.) than the high tin content whitemetals previously used. As used for lining bearing shells the thickness of the lead bronze is generally about 0·010 to 0·060 in.; this thin layer obviates the possibility of spreading under load or impact in service.

Comparison of Lead Bronze and Whitemetal. An interesting comparison of the bearing values of lead bronze and whitemetal has been made and is published in *R. and M. No.* 1424 of the Aeronautical Research Committee. The lead bronze consisted of 70 per cent copper and 30 per cent lead and was used as a thin lining to a steel shell. When tested in a ring-fatigue machine under a stress range of 19 tons per sq. in., the lead bronze lining after 15 million stress reversals revealed very little trace of cracking and its adhesion to the steel shell appeared to be unaffected by the test. Under similar conditions the best whitemetal linings showed distinct cracks after only 100,000 stress reversals and lost their adhesions almost completely after 15 million cycles. The coefficients of friction under forced lubrication conditions over a range of load of 1000 to 2500 lb. per sq. in. and a rubbing speed of 12 ft. per sec., from 60° to 100° C., were found to be practically identical for the two bearing metals, varying from 0·022 for the lowest load of 1000 lb. per sq. in. to 0·0008 for the higher load of 2000 lb. per sq. in. and 100° C. At a load of 2500 lb. per sq. in. with Mobiloil B the coefficient was about 0·0009.

The automobile and aircraft type lead bronzes are employed with alloy steel crankshafts, surface hardened by the electric-induction or nitrogen-hardening processes. As these alloys are not so plastic as the

whitemetals and therefore are not able to adjust themselves to slight dimensional differences in the journals, it is usual to allow greater clearances than with tin-base bearings.

The microstructure of the copper-lead alloys is governed largely by the rate of cooling. If cooled too slowly the lead has time to coalesce into larger particles while the matrix is in the pasty condition. If, however, the cooling is rapid, the lead becomes entrapped in a fine network of primary copper, and a much more uniform and finer dendritic structure results. Much attention has been given to the melting and casting technique and also to the effects of additions of small amounts of elements, such as silicon, zirconium and sulphur, with the object of preventing segregation of the lead and thus obtaining the fine structure which is associated with high fatigue resistance.

The copper-lead bearing alloys are cast at a much higher temperature than the whitemetals, namely at about 1100° C. as compared with 300° C. to 450° C. for the latter. It is therefore not possible to use tempered steel bearing shells as these would become softened. A good grade of mild or low nickel steel is usually employed for the bearing shells. After the alloy has solidified it is quenched in order to obtain the fine dendritic structure previously mentioned. Centrifugal casting methods are also employed with copper-lead bearing alloys.

The satisfactory bonding of these alloys with steel or gunmetal necessitates the preheating of the bearing shells to a temperature of 1050° C. to 1100° C. when the molten alloy is poured into the bearing shell jig and bonding occurs between the alloy and the metal of the shell. It is usual to coat the surface of the bearing shell with borax by immersion in a bath of the latter, when the film of borax left protects the metal against oxidation.

The bond between the lead bronze and steel shell is well illustrated in the photomicrographs reproduced in Figs. 115 and 116,* in which the dark constituent is the lead. The dendritic arrangement of the copper is clearly seen in Fig. 115. Fig. 116, taken at a higher magnification, shows that there is a narrow layer close to the steel which is practically free from lead. This absence of a brittle layer between the lead bronze and the steel is believed to account for the better performance of this bearing metal over whitemetal, which has a bonding layer of an intermetallic compound—probably one of tin and iron.

There are, however, several alternative methods of securing firm bonding of the alloy and bearing shell metal, which form the subjects of

* "Recent Developments in Bearing Metals," A. J. Murphy, *Proc. Inst. of Metals*, 1933–4.

patents. In one class of bearing the copper-lead alloy is cast on to steel strip and the latter after being cut to the required length is rolled to cylindrical or semi-cylindrical form to make the complete or half-bearing.

Some Possible Disadvantages. The adhesion of the lead bronze to the steel shell is often *examined by means of X-ray radiographs* of the finished bearings in the case of aircraft engines. In this connection

FIG. 115. LEAD BRONZE ON STEEL SHELL. × 100

FIG. 116. LEAD BRONZE ON STEEL SHELL. × 300

lead segregation is an occasional source of trouble. Another trouble that is associated with shortage of lubrication supply is that of "*lead sweat*" caused by the subsequent rise in temperature melting the lead, lead bronzes are generally regarded as being more sensitive to poor lubrication conditions than the other bearing metals. Moreover, the lubricating oil must be kept quite free of grit by careful filtering as the lead bronzes are more liable to scoring than the whitemetals and they do not possess the same "flow" properties. The free fatty oil content of the lubricating oil must be kept quite low in value, since lead bronze is known to be liable to corrosion with certain lubricants.

Practical Wear Tests. The high tin-base whitemetals previously used on Diesel engine vehicles were found by A.E.C. Ltd. to have a useful life of 10,000 to 16,000 road miles, whereas the lead-bronze bearings (centrifugally cast) gave useful mileages of 60,000 to 80,000;

in some instances engines fitted with such bearings have completed 130,000 miles of service without showing signs of wear.

Tri-fabricated Bearings. A more recent development is the employment of a three-layer bearing consisting of a steel shell of the normal type containing a lining of lead bronze of about 0·03 to 0·04 in. thick, on which is a thin lining of whitemetal or tin of about 0·001 to 0·002 in. thick. The whitemetal layer has proved an advantage in connection with the running-in period of the new bearing and its plasticity allows a certain amount of compensation for lack of alignment and slight inaccuracies in the initial bearing and shaft clearances. This type of bearing will withstand the same bearing pressures and speeds as the lead-bronze one, and experience has shown that the whitemetal is not worn away. A further advantage is the freedom from corrosion due to acid inhibitors in the lubricating oils of high-performance aircraft engines or from oil contamination agents whilst in service.

Aluminium Alloy Bearings

Aluminium alloys possess certain advantages for bearing purposes if employed under correct conditions in regard to journal or shaft materials, clearances, etc.

These alloys have very much better heat conductivities than other bearing alloys, namely, about five times that of whitemetals and three times that of steel, so that the bearings tend to run much cooler. Another advantage is their higher Brinell hardness, e.g. from 45 to 50, and the ability to retain this hardness at elevated temperatures to a greater degree than the other bearing metals previously considered. Moreover, they are not liable to corrosion as with lead bronze and cadmium bearing metals.

An alloy that has been used for bearing purposes is the Hiduminium R.R.56 alloy previously mentioned in Chapter III.

Another alloy is that known as *Chromet*, consisting of 90 per cent aluminium and 10 per cent silicon.

The R.R.56 alloy was not entirely without certain minor disadvantages, however, so that it has been superseded by another alloy, known as A.C.9, produced by the same manufacturers. This alloy has the following percentage composition limits: Sn, 5·7–7·0; Ni, 1·5–1·8; Cu, 0·6–0·9; Mn, 0·7–1·0; Si, 0·15–0·3; Fe, 0·2–0·45; Al, the remainder.

It has a specific gravity of 2·95 to 3·0, and a coefficient of linear expansion from 0° C. to 150° C. of 0·0000225. The thermal conductivity is 36 C.G.S. units.

As die-cast the bearings have a Brinell hardness of 45 to 50. They

are then heated to 180° C. for about 12 hours, when the hardness increases to 60 to 75; this hardness value is maintained with only slight diminution up to 150° C.

It is necessary to harden the shaft journals, either by induction, case-hardening or nitriding, when the bearings give entirely satis-factory service.

For softer shafts, down to about 280ʹ Brinell value, the silicon content of the alloy in question is increased to 0·4 per cent. The alloy,
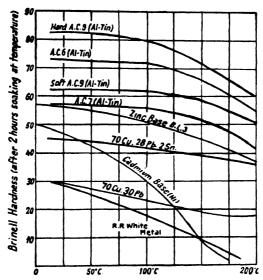
FIG. 117. ALUMINIUM-TIN BEARING METALS

after heat-treatment at 180° C. for 12 hours, has a Brinell hardness of 80 to 85, and is suitable for unhardened shafts.

In regard to *bearing clearances* these vary from 0·0012 to 0·00135 in. per inch diameter of shaft in the case of main bearings and 0·001 to 0·0013 in. per inch diameter for big-end connecting rod bearings.

The aluminium-tin bearing alloy A.C.9 has been used for the big-end bearings of Rolls Royce and also those of Bentley automobile engines, with entirely satisfactory results.

For the *main bearings* an aluminium-tin alloy having the following percentage composition limits has been used: Sn, 4·6–5·0; Ni, 1·6–2·0; Mn, 0·7–0·9; Sb, 0·4–0·8; Si, 0·45–0·6; Mg, 0·35–0·5; the rest, aluminium.

The properties of some of the more recent bearing alloys used in

TABLE 81

Properties of Bearing Alloys

Type	Maximum Stress Tons per sq. in. 15° C.	Brinell Hardness		Per cent Elongation 15° C.	Proof Stress Tons per sq. in., 1% Elongation 15° C.	Fatigue Range under Unidirectional Load Tons per sq. in. Skin Stress		Thermal Conductivity 0° C.–150° C.	Coefficient of Expansion 0° C.–150° C.	Specific Gravity
		15° C.	150° C.			15° C.	150° C.			
A.C.*	16·8	100	90	1·0	16·0	—	—	0·34 *	$22·0 \times 10^{-6}$	2·75
A.C.7	10·6	50	47	4·0	6·0	7·8	7·5	0·32	$22·3 \times 10^{-6}$	2·78
A.C.9 Soft	12·7	68	66	2·8	—	—	—	0·36	$22·3 \times 10^{-6}$	2·78
A.C.9 Soft, cold-worked, aged	18·3	85	82	3·0	14·7	—	—	—	$22·3 \times 10^{-6}$	2·78
A.C.9 Hard	14·3	82	80	2·0	—	—	—	0·36	$22·3 \times 10^{-6}$	2·78
A.C.17	10·2	42	36	12·5	4·5	3·0	2·2	0·29	$22·0 \times 10^{-6}$	3·0
Cadmium-nickel	6·5	48	17	14·0	3·0	—	—	0·17	$28·0 \times 10^{-6}$	8·6
70/30 Lead-bronze	11·3	30	28	12·3	4·7	—	—	0·62	$19·2 \times 10^{-6}$	9·8
R.R. whitemetal	4·8	30	9	8·5	1·9	1·7	<1·0	0·078	$22·0 \times 10^{-6}$	7·1
Zinc-aluminium alloy B.L.3	15·0	78	48	1·5	13·0	—	—	0·15	$26·0 \times 10^{-6}$	5·9

Aluminium-Tin Alloys (A.C.*, A.C.7, A.C.9 Soft, A.C.9 Soft cold-worked aged, A.C.9 Hard, A.C.17)

* Suitable as a replacement material for phosphor bronze in small bearings.

aircraft and automobile engines are given in Table 81,* whilst the hardnesses at temperatures up to 200° C. are shown in Fig. 117. The aluminium-tin alloys are here shown generally to be superior to the other bearing metals, both in regard to their hardnesses at various temperatures and in strength properties; moreover, they are only about one-third of the weights of most of the other alloys.

Aluminium alloy bearings are being used in the United States where it has been found that the alloys employed have a higher fatigue resistance than the best lined steel shell bearings, a high resistance to corrosion by breakdown products of the lubrication oil, and give a cheaper construction of the bearing since only the single metal is used. It is also claimed that these alloys have a sufficiently low coefficient of friction. The bearing must be properly cast and the correct alloy used, with a minimum thickness of 0·09 in. For the main and big-end bearings permanent mould castings are used, whilst rolled sheet is employed for the camshaft bearings.

Cadmium Bearing Metals

Cadmium is a soft metal resembling tin in its mechanical properties, and it has been shown to be suitable as a base-metal for bearing alloys. Copper and cadmium form a eutectic with 1·2 per cent copper, having a melting point of 321° C.; its constituents are a copper-cadmium compound $CuCd_3$ and cadmium with a little copper in solid solution.

An alloy having 3·1 per cent copper with the addition of 0·2 per cent magnesium to prevent oxidation and give a silver-white appearance has been found† to have advantages over tin-base whitemetals in regard to its ability to withstand heavier bearing pressures and higher working temperatures. It has, in addition, superior wear and distortion resistance. The alloy in question had a Brinell hardness of 48, compressive and tensile strengths of 27 and 10 tons per sq. in. respectively, and a freezing range 60° to 80° C. above that of ordinary tin-base bearing alloys, i.e. 378° C. to 315° C. as compared with 320° C. to 243° C. It has a similar frictional coefficient to tin-base whitemetals. On the other hand, this cadmium-copper alloy was inferior in regard to ductility as indicated by its percentage elongation of 3·1 compared with 12·5 for a strong tin-base alloy. It also has a greater shrinkage than the latter metal, so that special precautions must be taken to

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* "High Output Aircraft Engines," E. W. Hives and F. L. Smith, *S.A.E Journ.*, March, 1940.

† "Cadmium-base Bearing Metals," A. S. Gill, *Metal Industry*, 14th June, 1935.

ensure effective bonding with the bearing shell; otherwise it is liable to crack and loosen in its shell.

The load-carrying capacity and ductility of the alloy mentioned has been improved by reducing the copper content and increasing that of the magnesium. An improved bearing metal of this class has the following percentage composition: cadmium, 97·5; copper, 1·5; magnesium, 1·0.

The physical and mechanical properties of this alloy as well as those of a high grade tin-base whitemetal used for comparison purposes are given in Table 82.

TABLE 82

PROPERTIES OF CADMIUM-BASE AND TIN-BASE BEARING ALLOYS

	Cadmium-base	Tin-base
Compressive strength (tons per sq. in.) .	34·6	10·7
Tensile strength (tons per sq. in.) . .	11·9	5·5
Elongation, per cent	11·0	12·5
Brinell hardness (500 kg. load: 7·5 mm. ball)	57	23
Relative degree of bending before fracture	100	167
Relative loading to produce fracture by bending	100	56
Relative rate of wear in a bearing .	100	258
Specific gravity	8·4	7·4
Freezing range	338°–315° C.	285°–247° C.
Shrinkage relative to steel (mils per 1 in. diameter)	9·5	6·3

Although the alloy whose properties are shown in Table 82 has about 30 per cent greater shrinkage than the whitemetal, it has been found possible to obtain a satisfactory bond with steel and bronze bearing shells by tinning the surfaces of these with a *cadmium-zinc solder*, namely, the eutectic alloy of 82 per cent cadmium and 18 per cent zinc, which melts at 270° C.; other cadmium-zinc alloys with 7 to 50 per cent zinc also give satisfactory results, but the eutectic mentioned was slightly superior. The shearing strength of this bonding alloy for the cadmium-copper bearing metal and steel shell is about 7 tons per sq. in.

In regard to the *frictional coefficients*, for the bearing alloy mentioned in Table 82, these were 0·0018, 0·0012 and 0·0009 at 60° C., 80° C. and 100° C. for a bearing load of 2500 lb. per sq. in. Whilst the two former values are the same as for tin-base whitemetals, at 100° C. the coefficient is only one-half that of the whitemetals.

The results of abrasion tests indicate that *the rate of wear of the cadmium-base bearing metal* is only about 40 per cent of that of a high-grade tin-base whitemetal.

Cadmium-silver Bearing Alloys

Alloys consisting for the most part of cadmium with small amounts of copper and silver have been found to be satisfactory for bearings subjected to relatively high bearing pressures and speeds; they have been employed in the United States in recent times.

A typical alloy contains 97·6 per cent cadmium, 1·9 per cent copper and 0·5 per cent silver. In some instances the copper is replaced by

FIG. 118. PURE CADMIUM.
× 67

FIG. 119. CADMIUM-SILVER
ALLOY. × 140

about 3 per cent of nickel. The small amount of silver improves the casting quality and refines the grain; the hardness of the cadmium is also increased.

These alloys have a Brinell hardness of 35 to 38 at 20° C. and 5·5 to 6 at 200° C. Although the Brinell hardness is much lower at elevated temperatures than that of the lead bronzes, it is from 2 to 3 times greater at 100° C. to 200° C. than the best high-tin whitemetals.

Cadmium-silver bearings are being used for bearing loads of 2000 lb. per sq. in. and pressure-velocity values of 65,000 to 70,000.

In certain two-cycle Diesel engines* bearing pressures as high as 3,300 lb. per sq. in. have been employed with cadmium-silver bearings whereas when the best Babbitt metals were used, the bearings failed after relatively short periods with loadings of 1600 lb. per sq. in. Other tests made in the instance of an automobile engine which normally ran at exceptionally high temperatures showed that the

* *The Machinist*, 12th June, 1937.

cadmium-silver bearings lasted from 10 to 15 times as long as the Babbitt ones.

As compared with tin-base whitemetals cadmium-silver alloys have greater load-carrying capacity, higher melting points, namely, about 70° C. higher, lower coefficient of friction and greater strength and hardness at elevated temperatures. It is necessary, however, for the steel shafts with which this alloy is used to have a hardness of at
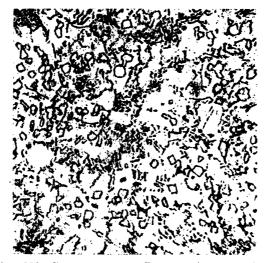
FIG. 120. CADMIUM-NICKEL BEARING ALLOY. × 150

least 250 Brinell. In regard to bearing clearances cadmium-silver alloys employ the same values as for high-tin whitemetals. These alloys are used with steel shells as in the case of whitemetals and accurate fitting of the shells in their housings, preferably with ground finish, is essential. They are cheaper to manufacture than lead-bronze bearing alloys and require less bearing clearance than for the latter. The corrosion resistance of cadmium-silver alloys is superior to that of lead bronze.

Cadmium-nickel Bearing Alloys

Cadmium-nickel alloy bearings containing 1·3 per cent of nickel and the rest cadmium have been used in the United States for high-duty purposes under the name of "*Asarcoloy*." Fig. 120* is a photo-micrograph of this alloy and shows that the structure comprises angular

* Bureau of Information on Nickel.

crystallites uniformly dispersed throughout the mass of the metal. These crystallites consist of a hard intermetallic compound of cadmium and nickel, the matrix being substantially a eutectic of cadmium and this same compound.

The densities of the hard particles and the matrix are almost identical and there is therefore no tendency for the constituents to segregate during casting, such as is sometimes experienced in the white-metals. The photomicrograph brings out well the absence of this segregation and the evenness of the structure. The latter, it will be seen, is of the type recognized as necessary in a bearing metal, viz. hard particles embedded in a soft matrix. The soft matrix gives a degree of self-alignment, thus enabling the bearing to adapt itself to irregularities, and the hard particles are sufficiently hard to give good wear resistance without scoring the shaft; at the same time, they stand out in relief from the matrix, thereby producing channels through which the oil can freely run over the surface of the bearing.

The alloy in question has a coefficient of friction varying from 0·0024 at 60° C. under lighter loadings to 0·0009 at 100° C. for heavier loadings.

The compression strength of the cadmium-nickel alloy is indicated by the results of tests on cylinders of $\frac{1}{4}$ sq. in. cross-sectional area and $\frac{1}{2}$ in. long which required a stress value of 12 tons per sq. in. to compress them to one-half their length as compared with 7 tons per sq. in. for high-grade Babbitt specimens of the same dimensions.

The melting point is 310° C. as compared with 230° C. for a comparable high-grade tin-base whitemetal.

The tensile strengths at 28° C., 100° C. and 200° C. of the alloy were 7·2, 6·8 and 1·47 tons per sq. in. respectively, whereas for high-grade Babbitt the values at these temperatures were 4·5, 5·6 and 0·8 tons per sq. in. respectively.

The Brinell hardnesses at these temperatures for the cadmium-nickel alloy were 32·5, 17·5 and 7·5; and for the Babbitt, 23·5, 10·5 and 3·5 respectively.

The steel bearing shell after thorough cleaning and pickling in hydrochloric acid and then in zinc chloride is tinned to ensure good adhesion of the cast-on bearing alloy. The bonding metal bath is kept at 450° C. and the shell immersed in this immediately after drying; this ensures correct tinning. The cadmium-nickel alloy is poured at 380° C. to 400° C. into the bearing shell jig. The bond thus obtained is exceedingly strong and will withstand severe engine operating conditions without loss of adhesion. Tests made on the bond strength showed that the shear stress was 3·95 tons per sq. in. as compared with 2·6 tons per sq. in. for Babbitt.

Cadmium-nickel alloy has been used successfully in the United States for some time for big-end connecting rod bearings of automobile engines. Fig. 121 illustrates a cadmium-nickel bearing after exacting tests made in an automobile engine over a very long period; other alloy bearing metals tested over a similar period failed by flaking.

Beryllium-copper Bearing Alloy

An alloy of copper with 2·25 per cent of beryllium has been used as a hard bearing metal in place of bronze, and it has shown about
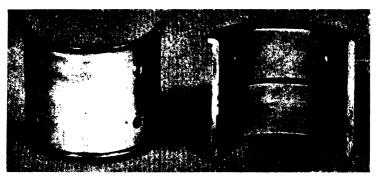
FIG. 121. NICKEL-CADMIUM ALLOY BEARING IN GOOD CONDITION AFTER SEVERE BREAKDOWN TEST

five times the wear resistance of the latter alloy under similar conditions of use, namely, with steel shafts. It appears to have a film-forming and self-lubricating property, although it has been shown that high rubbing speeds combined with heavy bearing pressures can cause seizure between this alloy and its steel shaft. In dry rubbing tests under a load of 10 lb. per sq. in. against a flat steel rotating disc, beryllium-copper specimens glazed quickly and wore evenly, whilst bronze specimens under identical conditions wore more rapidly and less evenly.

The 2·25 per cent beryllium-copper alloy in the soft condition has a tensile strength of 35 tons per sq. in. with 45 per cent elongation. When heat-treated to the fullest extent the tensile strength is increased to 90 tons per sq. in. with 2 per cent elongation.

Monel Metal Shaft Bearings

The problem of the most suitable material to use as a bearing for Monel metal is a question of the material that will most satisfactorily meet the service conditions entailed.

The whitemetal groups of bearing alloys are accepted as being suitable for medium speeds and loads, or high-speed and low-load service. It has been found that a Monel metal journal runs as well in any typical tin or lead-base Babbitt-lined bearing as does a steel journal.

As the load increases, harder alloys than the whitemetals are required and recourse is made to the use of bronzes of various kinds. Provided oil lubrication is ample, no trouble should be experienced when employing Monel metal shafts. If, however, lubrication is known to be poor, the high lead bearing bronzes containing from 15 per cent to 25 per cent lead with under 10 per cent tin are to be recommended. This latter type of alloy can actually be employed for Monel metal with water lubrication.

In connection with the recently developed self-lubricating bearing alloys and laminated plastic materials, there is no reason to believe they should not be suitable for Monel metal.

Rubber bearings have proved very successful for Monel metal shafts for underwater applications, such as stern tubes and outboard brackets on motor boats, and it is also interesting to note that a synthetic rubber bearing material, now available, is suitable for use with oil instead of water.

Moulded Metallic Powder Bearings

A more recent application of powder metallurgy consists in the moulding under pressure of bearings from mixtures of metallic powders, such as copper and tin, with or without the addition of graphite powder. Bearings can thus be produced for medium loads and low speeds with good mechanical properties, and relatively cheaply, to moulded dimensions within 0·001 in. of required size. Usually the bearing portion is finished to size by reaming or drifting.

A typical mixture consists of 90 per cent sharp-grained powdered copper and 10 per cent powdered tin. The mixture is moulded in self-ejecting presses under pressures up to about 20 tons per sq. in. and the moulded product is afterwards sintered, i.e. furnace heated in a reducing atmosphere at about 700° C., followed by quenching in lubricating oil. The density of the moulded material is from 70 per cent upwards of the equivalent solid density. The bearings can thus be made slightly porous to hold lubricating oil, and are therefore claimed to be "self-lubricating." Further, any oil touching the bearing surface is readily absorbed, oil grooves or holes being unnecessary.

The Compo H bush* is made from pure metallic powders,

* British Bound Brook Bearing Co.

die-pressed to shape within the limits of $\pm$ 0·0005 in. diameter; other dimensions are held within $\pm$ 0·001 in.

A typical percentage composition is as follows: copper, 88·0; tin, 9·7; graphite, 1·4; other material, 0·9. The crushing stress is about 30 tons per sq. in. and specific gravity 5·8 to 6·5. The recommended maximum bearing load is 2000 lb. per sq. in.

Typical applications include bearings for small electric motors, vacuum cleaners, dynamos, fan spindles, rocker arms, gramophone
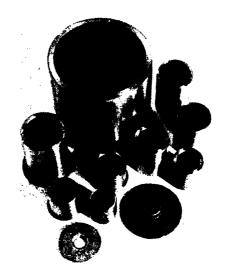
FIG. 122. EXAMPLES OF SELF-LUBRICATING BEARINGS
(Copper Development Association)

motors, domestic machines, clocks, compressors, electric drills, switchgear, aircraft lever bearings, motor car shock absorbers, etc.

Moulded bush-type bearings of this class should be inserted into their housings with a supporting mandrel in order to preserve accurately the size and condition of the bearing, thus obviating any further machining or finishing. The standard housing fits for bushes are given in a Specification issued on the Institution of Automobile Engineers' Data Sheet No. 186.

Fig. 123 illustrates the method of inserting the bush in its housing. The insertion plug is made a tight fit in the bush, and its diameter is made slightly greater than the bore of the bush itself.

Lead bronze bearings can be made from the powdered metals in a

somewhat similar manner, although several difficulties have been experienced in obtaining proper diffusion of the lead throughout the copper and the avoidance of segregation effects. The most successful method as yet appears to be that in which the lead powder particles are first coated electrolytically with copper and the mixture of this coated powder and copper powder is then pressed into a sheet and sintered in a hydrogen atmosphere at 900° C. for 20–35 per cent lead and 750° C. for 45–55 per cent lead. This lead-bronze product will bond well with copper and bronze shells, but in the case of steel it is necessary first to tin-coat the latter.
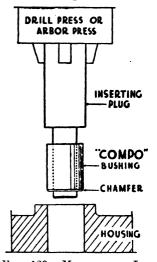
Bearings of Powdered Nickel Alloy

A method of making automobile engine bearings of the steel shell-backed type developed by General Motors Co., U.S.A., employs nickel and copper powders.

In order to secure a perfect bond between the Babbitt and steel a powdered metal matrix consisting of copper and nickel powders is used.

Both tin-base and lead-base Babbitts have low resistance to fatigue. Experience shows that cracking and actual breaking out of the bearing surface is more likely to occur if the Babbitt layer is thick. Thin layers are, however, difficult to use unless the bonding is very secure. The new process utilizes the technique of powder metallurgy to sinter and braze to the steel back a matrix composed of a mixture of 60 per cent copper and 40 per cent nickel powder. The porous structure produced in this way gives secure support to the Babbitt, both chemically and by mechanical interlocking. It is thus possible to utilize a layer of Babbitt only 0·002 in. thick, which is completely free from any fatigue effects. In the manufacturing process strips of steel pass through the various operating machines in turn, the process thus being continuous.

Fig. 123. Method of Inserting Moulded Metallic Powder Type Bearing Bushes

From the Babbitting machine the strip goes to a rolling machine fitted with pinch rolls to impress a positive tension on the strip. Sufficient Babbitt is removed to give the required total thickness from the underside of the steel back to the top of the bearing surface. The final stage is a stamping and blanking press which cuts the strip

into blanks of the right size for the subsequent forming of the half shells.

Graphite Bearing Metals

A type of bearing metal sometimes known as *spongy bearing bronze* has resulted from investigations into the effects of graphite upon certain alloys. These metals contain graphite uniformly distributed
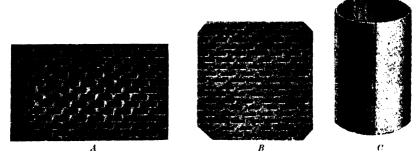
FIG. 124. THE CLEVELAND GRAPHITE BUSHING

A = Plate after passing through the dies.
B = After second operation through the flat rollers.
C = The finished bushing.

throughout their composition, and when used for bearings they are therefore self-lubricating.

Such bearings are applicable to non-accessible slow-running machinery, both marine and stationary.

Two well-known graphite bearing metals are Genalite* and Durex.†

Genalite has the following composition: copper, 70·18; tin, 13·72; lead, 9·00; iron, 0·22; phosphorus ,0·055; graphite (C), 5·35; and zinc, 1·475 per cent.

It has a Brinell hardness of 21·6.

Durex is made in two grades for lighter and heavier duties respectively. Both are copper-tin alloys containing graphite.

The former alloy has the following composition: copper, 83·2; tin, 10·0; graphite (C), 4·4 to 4·7; impurities, 0·60 per cent.

It has a specific gravity of 5·4. The Brinell hardness is 30 to 40. The modulus of elasticity is 2,500,000 lb. per sq. in. It has a volumetric oil absorption of 25 per cent, and a linear expansion of 0·00094 in. per inch per 100° F. (38° C.).

This alloy is used for porous bearings and, as stated, it possesses

* Manufactured by General Electric Co., Schenactady, U.S.A.
† Manufactured by General Motors Research Co., Dayton, Ohio.

oil absorbing properties. It is used for certain automobile chassis bearings and for gun bearings. It is porous to the extent of 15 per cent oil absorption by volume.

Another interesting form of graphite-bronze bearing is that marketed under the name Cleveland Graphite Bushings (Fig. 124). The bushes are made, by a special rolling process, from flat bronze plates. The plate blanks are passed through dies and indentations rolled into them, after which they are passed through flat rollers, the high spots

FIG. 125. ENLARGED SECTION OF INDENTATION SHOWING LOCKING RECESS FOR GRAPHITE .LUBRICANT

formed by the indentations being rolled over and forming dovetailed shaped recesses. Hot graphite is then rolled, under pressure, into these recesses, after which the plate is rolled into its circular bush form to an accuracy within the limits of two-thousandths of an inch. The forming of the circular bush from the flat plate still further increases the dovetailed form of the indentations, locking the graphite securely in. The graphite-filled indentations of the Cleveland (dovetailed) bushing form a large percentage of the total bearing surface of the bush, and the process of manufacture makes possible bushes with walls of practically any thickness. These bushings with very thin walls are specially suitable for fixing to parts such as bearings in concentric rocking shafts, brake compensating shafts, pedal and rocker shafts, controls, etc.

The British Bound Brook oil-less bearing, shown in Fig. 126, consists of a high-grade bronze casting in the interior of which grooves are cast. Before final machining is carried out the graphite compound, indicated by the black lines, is forced into the grooves under hydraulic pressure and the whole bearing is then subjected to heat-treatment; afterwards the bearing is machined to size. This type of bush is

employed for reasonably slow revolving shafts or for intermittent service fast moving shafts. Such bearings have been used for automobile starting motors, steering columns, clutch spigots, brake rocking shafts, tackle-blocks, cranes and hoists.

Notes on Oil-impregnated Bearings

The porous bronze bearings, such as Oilite and Bound Brook, retain about 30 to 40 per cent of their volume of lubricating oil, but they may be re-impregnated by heating to a temperature of 110° C. to 120° C. in a bath of lubricating oil of suitable viscosity, namely, 1500 secs. Redwood at 70° F.

The bearings should be left about 0·002 to 0·003 in. undersize so that after being pressed into their housings they can be brought to final size by means of a polished arbor forced through them or with a broach. The bearings can be made a press fit in most die-castings or can be cast in place where pressure die-castings are employed; the un-impregnated bearings are used in such applications.

FIG. 126. BEARING BUSH WITH GRAPHITE INSERTIONS

For speeds of 500 to 1000 r.p.m. the bearing pressures for a 1-in. diameter hole bush are 125 lb. per sq. in., falling to about 60 lb. per sq. in. for a speed of 4000 r.p.m. For intermittent oscillation purposes bearing pressures up to 3000 lb. per sq. in. are permissible. The smaller sizes of bush will withstand higher bearing pressures than the larger ones. Thus at 2000 r.p.m. the 0·5 in. bush will operate with 110 lb. per sq. in. and the 2·0 in. one with 50 lb. per sq. in.

Laminated Bronze-steel Bearing

A more recent type of bearing, known as "pre-cast bearing bronze on steel," consists of a bronze alloy containing 80 per cent copper, 10 per cent tin and 10 per cent lead. The alloy is cast in bar form and the centre of each bar is drilled out. The borings obtained are reduced to powder, treated in a hydrogen furnace to get rid of any oxides, and then firmly bonded to strip steel. The resultant product is stated to be much stronger and more resistant to impact effects than ordinary cast bronze and to have a lower coefficient of friction. The bearing can also be made as a graphite-impregnated one by mixing graphite powder with the bronze powder before the bonding operation. This

bearing material is available as finished bearings, washers, strips or rolls up to 400 ft. in length.

Bakelite and Plastic Material Bearings

Resin-bonded fabric materials of the phenol-formaldehyde kind have been used with satisfactory results for bearings employed under certain conditions, more especially those for heavily loaded purposes such as for rolling-mills, propeller shafts, paper machinery, underwater bearings and pumps handling various kinds of liquids, including most acids and mild alkalis.

The impregnated laminated fabric material, such as Bakelite Laminated, is employed for such bearings and the resultant product has been shown to possess strength, density, smooth bearing surface and high load-carrying capacity, without any scoring tendency.

The most satisfactory lubricant appears to be water mixed with a water-soluble oil, free from acid or alkali; the water serves to carry away the friction heat since the laminated material is a poor conductor of heat. Water alone can also be used, but the bearing loads allowable must then be reduced. Thus, with the soluble oil lubricant bearing pressures of 4000 to 5000 lb. per sq. in. can be used, whilst for water alone the pressures should not exceed about 2000 lb. per sq. in.

Physical Properties. The phenol-formaldehyde bonded woven cotton cloth laminated material used for bearings is non-hygroscopic, hard and unaffected by dilute solutions of most acids and alkalis. It has a specific gravity of about 1·35 and a tensile strength across the face in two directions of between 4 and 5 tons per sq. in.,* and across the laminations of 2 tons per sq. in. The shear stress through the laminations is from 4 to 5 tons per sq. in. The compressive stress at right angles to the laminations is about 18 tons per one inch cube. The Brinell hardness, using a load of 125 kgm. on a 5 mm. ball, is between 33 and 37.

The coefficient of thermal expansion through the laminations is 0·00006 to 0·0008 per °C.; along the laminations it is about 0·00004.

The coefficient of friction using water lubrication is about 0·004 for bearing pressures of 1000 to 4000 lb. per sq. in. and rubbing speeds of 500 ft. to 3500 ft. per min.

Bearing Pressures. The bearing material can be given a high degree of surface finish and if used with polished journals can be used in different designs for light loads up to 500 lb. per sq. in., medium loads from 500 to 1500 lb. per sq. in., and extra heavy loads of 4000 lb. per sq. in. and above.

* Certain grades give tensile strengths up to about 15 tons per sq. in.

In regard to the *rubbing speeds*, the following values have been given* for water lubricated bearings corresponding to the previously mentioned groups of bearing pressures: Light loads, 100 ft. to 4000 ft. per min.; medium loads, 150 ft. to 3000 ft. per min.; heavy loads, 250 ft. to 2500 ft. per min. Extra heavy loads are usually associated with low rubbing speeds and with grease or oil lubricants; alternatively
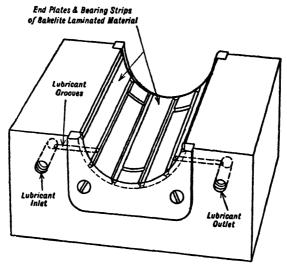
FIG. 127. HEAVY-LOAD BAKELITE LAMINATED BEARING CONSTRUCTION

soluble oil and water can be employed in instances where the loads are not excessive.

Advantages and Disadvantages. The advantages claimed for laminated material for bearings are summarized as follows: (1) Lightness of the bearings and easy handling; (2) smooth bearing surface; (3) good load-carrying capacity; (4) high impact-resistance; (5) good strength properties; (6) easily lubricated by most media; (7) non-scoring properties; (8) low coefficient of friction; (9) low modulus of elasticity; (10) hard wearing qualities; (11) reduced maintenance costs in service; (12) reduced lubrication costs; (13) much quieter operation.

The disadvantages are as follows: (1) Poor heat conductivity, thus necessitating greater quantity of lubricant to carry off surplus heat; (2) low temperature range of operation; (3) limited applications in

* "Synthetic Materials for Mill Bearings," C. D. Phillippe, *The Engineer,* 2nd February, 1940.

practice; (4) greater initial cost; (5) when finished with, no scrap value.

Typical Applications. Bakelite laminated and similar plastic bearing materials have been widely used for rolling mill bearings; in Germany about 80 per cent of the rolling mills have this type of bearing.

The cages of ball bearings are frequently made of plastic material. Fig. 127 illustrates a typical Bakelite bearing and shows the metal
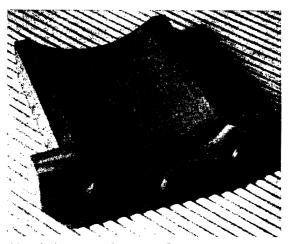
FIG. 128. A ONE-PIECE BAKELITE LAMINATED HALF-BEARING

housing with deep grooves running parallel with the axis of shaft. In these grooves strips of laminated Bakelite are fitted, the built-up bearing being afterwards machined to size. End plates are provided to prevent excessive leakage of the lubricant and also to take any end thrust. The lubricant is fed into the bearing through the drilled passage shown in Fig. 127, and it leaves by a similar one on the opposite side.

In regard to this design of bearing it is claimed that the power consumption is appreciably less than for metal bearings employed for the applications previously mentioned, whilst in many cases the bearings have had up to ten times the life of the metal ones for which they have been substituted. Experiments have been made with smaller synthetic resin bearings with a metallic filler, but these were found to be little better than the plain resin material due to lack of bonding of the resin and metal. The use of shredded fabric in place of metallic particles has given better results, but in order to obtain the desired strength the woven fabric material should be wound on a mandrel of the proper size before impregnating with the synthetic resin. Such

bearings have been found suitable for light loadings and moderate speeds, but are not likely to rival the whitemetals and other modern bearing alloys.

Rubber Bearings

Moulded rubber of special composition, enclosed in a metal housing, is now used for certain classes of bearings, namely, water-lubricated

A   **B**
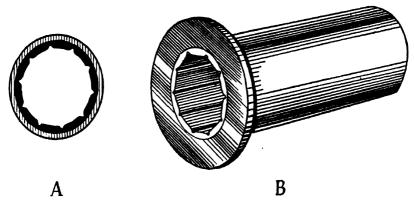
FIG. 129. TYPICAL RUBBER BEARING FOR UNDERWATER USE

A—End section. *B*—Perspective view.

bearings for marine and similar purposes. A tough resilient rubber compound is employed for the purpose and the bearing (Fig. 129) is designed so as to form a series of longitudinal concave strips with grooves between. This type has been used with satisfactory results for stem and A-bracket bearings for ships' propeller shafts, for centrifugal pumps, dredging machine bearings, deep well pumps, mining, sand and gravel plant. The net coefficient of friction of the rubber used is 0·010 to 0·005. High rubbing speeds with medium pressures are permissible.

The rubber is vulcanized on to the metal and an adhesional strength as high as 600 lb. per sq. in. is obtained. The bearings are moulded to size, with suitable allowances for rubber shrinkage so that no subsequent machining is necessary; the shrinkage allowance is $\frac{5}{32}$ to $\frac{7}{32}$ in. per foot. An alternative to the longitudinally-fluted type of bearing is one with a spiral groove.

CHAPTER VIII

DIE-CASTINGS

IN view of the importance of the die-casting process from the point of view of many of the non-ferrous metals and alloys described in this work, it is proposed to give a brief outline of the methods and the die-casting alloys employed.

The term "*die-casting*" applied to the casting of metals under pressure in metal moulds is known as *pressure die-casting*, but is also frequently used for castings made in metal moulds, where the molten metal flows by gravity only into the moulds; the more correct term in the latter case is "*gravity die-casting*."

Die-casting is employed where a large number of similar castings are required; in the ordinary way it does not pay to make the metal moulds for a number of die-castings smaller than, say, 500 to 1000. For smaller numbers of large die-castings the mould may, however, be relatively less expensive than for a greater number of small die-castings.

Die-castings possess the following advantages over sand-castings—

1. They are much more accurate. In the case of pressure die-castings they can be made sufficiently accurate for most purposes so that machining costs can be saved.

2. They can be produced more quickly than sand-castings, so that production can be speeded-up.

3. Inserts, studs, bushes, and similar objects in different metals can be cast in position.

4. Holes can be left during the casting process to a high degree of accuracy, thus obviating drilling. In a similar manner threads can usually be cast with sufficient accuracy in the case of outside-threaded parts.

5. The general finish of die-castings is such that, generally speaking, no further work is required on the castings; they may, however, be plated, polished, or painted for certain purposes.

It should be pointed out that with gravity die-castings the accuracy is not so great, and machining is usually necessary. The drawbacks of the die-casting method may be enumerated, briefly, as follows—

1. The process only pays where the number of castings required runs into some thousands, on account of the cost of the dies and of the machine charges.

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2. It has hitherto been limited to a few groups of metals of relatively low tensile strengths—usually about 8 to 10 tons per sq. in. (maximum).

On the other hand, recent advances with aluminium alloys have shown it possible to die-cast certain alloys of much greater strength than the tin-zinc and lead-base alloys usually employed. As an example, the case of *die-cast petrol engine pistons* may be mentioned; it is now possible to produce die-cast pistons in high-strength aluminium (such as the R.R. class) and magnesium alloys (e.g. Elektron). More recently yellow brasses and aluminium bronzes have been successfully employed for die-castings.

Die-casting can be done with automatic machines, so that a relatively large number, e.g. 300 per hour in the case of small castings, can be produced in a shorter period than with sand-castings.

It is necessary to produce a larger number of castings in order to employ automatic machines economically than in the case of hand-operated machines; thus it is seldom economical to produce less than 10,000, say, with an automatic machine, whereas from 800 to 1000 may prove a profitable proposition with a hand-operated machine.

Perhaps the most important feature of die-casting is its ability to make complicated shapes of casting with thick and thin walls or webs, without the attendant difficulties with sand-castings. Thus walls, webs, or partitions can be die-cast to thicknesses down to $\frac{1}{16}$ in., and even less; with tin and lead alloys thicknesses down to $\frac{1}{32}$ in. can be obtained. It is also a fairly straightforward matter to die-cast small gearwheels, bevel pinions, racks, worms, and worm-wheels which will mesh with one another with sufficient accuracy for most purposes. Such gears are widely used for instruments and apparatus where they experience light pressures and intermittent use for short periods.

The fact that it is possible to cast "inserts" of other stronger metals into castings of weaker metals is an advantage from the point of view of wearing parts, e.g. friction surfaces, studs, screw-threads, and bearings; in such cases a good deal of the expense due to machining and pressing is avoided. One drawback of die-castings in the inferior strength metals and their alloys is that, apart from low tensile strengths these metals or alloys have relatively low melting points. Thus, the tin-base alloys have melting points of 230° C. to 300° C. On the other hand the newer zinc-base die-casting alloys such as "Mazak" have melting points of about 400° C.

The aluminium die-casting alloys are cast at about 700° C. The highest melting point alloys hitherto used for die-castings are brasses and aluminium bronzes, the pouring temperatures for which are about 1000° C. to 1100° C.

Some typical examples of die-cast parts are illustrated in Figs. 130, 131, and 132; most of these have been made in aluminium, brass, and zinc-base alloys. These alloys are now very widely employed
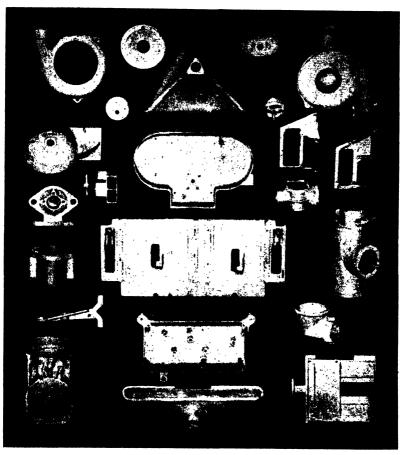
FIG. 130. SOME TYPICAL EXAMPLES OF ZINC-BASE AND YELLOW BRASS DIE-CASTINGS

for die-cast bearings, parts of instruments, automatic machines, meters, cash-registers, telephone and electrical apparatus, and wireless fittings.

It can be stated that, but for the relative cheapness of the die-casting methods, the majority of the items previously mentioned would cost appreciably more.
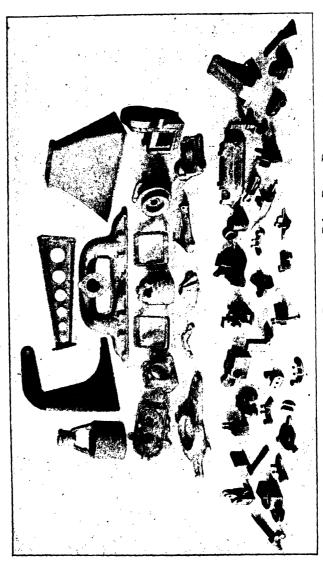
FIG. 131. *Above*, ALUMINIUM DIE-CASTINGS. *Below*, BRASS DIE-CASTINGS

(*Messrs. J. Stone, Ltd.*)

Accuracy of Die-castings

In tin- and lead-base alloys a high degree of accuracy can be obtained, viz. approximately 0·001 in. per linear inch. On small parts this refinement is exceeded, variations of dimensions being of the nature of 0·0002 in. For zinc alloys 0·002 in. and aluminium alloys 0·004 in. per linear inch are more usual figures. With the higher temperatures required for the copper-base alloys, brasses, and aluminium bronzes, a high tolerance must be allowed, as the dies wear at a greater rate.

A draft or slight taper is necessary in order to allow the finished casting to be ejected from the die. This varies from 0·0005 in. per inch, in tin-base alloys, to 0·010 in. per inch in aluminium and other high melting point alloys.

Pressure Die-casting

The principle of the apparatus used is simple, and can be described as follows: Imagine an ordinary teapot filled with molten metal. To the spout of the pot is fixed the die, and into the top, in place of the lid, a metal plunger is introduced. Sharp application of pressure on the top of the plunger will force the metal up through the spout into the die, which is capable of opening readily for the release of the casting thus produced. A small hand-operated machine, patented in 1872, worked exactly on the lines described, and, although modern machines on the plunger lines are, of course, much more complicated, the principle is the same.

The pressures employed range from 100 to 6000 lb. per sq. in., depending upon the nature of the alloy and the type and size of casting to be produced.

The general equipment of the modern die-casting machine includes several melting pots, generally gas or oil-heated, usually of cast iron, which are placed close to the machine so that the molten metal can easily be poured. The actual casting machine has also a reservoir containing metal, which is kept hot by gas burners, enclosed in a firebrick lined chamber. The plunger is operated by means of a long lever, and the pump with the plunger is attached to the reservoir. A plate which swings on a hinge is brought into contact with the spout, and fastened into position with clips. The mould or die is also fastened to this plate, and consists of at least two parts which are held together with a toggle joint which admits of quick release, thus parting the mould after the metal has been poured. The parts of the mould are kept in register by means of dowels. A rack and screw mechanism is used for removing the cores. Internal threads are produced by screwed
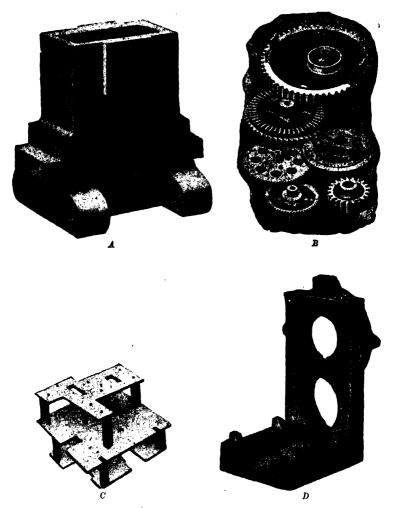
FIG. 132. SOME FURTHER EXAMPLES OF DIE-CASTINGS IN
VARIOUS METALS

A = A large casting weighing 4 lb. C = Intricate taximeter housing.
B = Toothed wheel castings. D = A machine bracket.

cores, and external threads by screwed collars. Vents are placed judiciously at intervals to enable the air expelled by the incoming metal to get away, and the success of any particular casting often depends upon the skill used in venting the die. The vents are usually thin, flat apertures, through which air, but not the molten metal, is able to penetrate.

The operation of casting in a plunger type machine is as follows: After the reservoir has been filled with molten metal and the lip of the nozzle cleaned from any dross, the die itself is prepared. This is opened, cleaned, oiled, and sometimes dusted with French chalk, cores are racked and screwed in position, and inserts or bushes are placed as required. It is then closed, and by means of the plate already described is brought up against the nozzle of the reservoir and carefully pressed closely and accurately to it. The plunger is then operated by a long lever, the arm of this being moved by the workman. It is doubtful if there is any one definite kind of stroke of the plunger which is the correct one for properly forcing the metal into the die. The kind of pull on the lever is very important, but while in some cases a sharp stroke is necessary, in others a good long follow-through pull is the best.

The casting completed, the mould is opened after severing and removing the spout. The removal of the casting is effected by advancing a set of ejector pins, which lies flush with the surface of the die during the casting operation, and the casting is gently pushed out immediately after it has solidified. Nearly all zinc-base die-castings just show the marks of the ejector pins. The casting is now ready for trimming, and, if required, for polishing, plating, etc.

The Dies

Considerable ingenuity is often required in connection with the design of the dies for die-casting machines; in addition great accuracy and a knowledge of the casting properties of various alloys are essential.

It is necessary for the die-designer to draw largely on his experience in connection with the thickness of the die metal, its shape, the positions of the gate and vents, and the operation of the ejector.

The die itself is usually made in two parts, namely, a stationary cover and a movable ejector. All cores employed must either be tapered or collapsible for withdrawal. The dies for new designs of parts to be die-cast frequently have to be completed by a trial and error method after the first approximately accurate trial casting has been made; this is one of the reasons why the dies are frequently expensive.

In regard to the material used for the dies, carbon steels have been found satisfactory for low melting point alloys of the lead-, tin-, and zinc-base class. Steels of 0·4 per cent carbon content give exceedingly long periods of service, provided they are suitably normalized. On the other hand, *for the higher melting point alloys*, such as those of aluminium, *alloy steels* have been found to be necessary. The alloy steels usually employed for this purpose include chromium, nickel-chrome and chrome-vanadium grades, suitably heat-treated; non-shrinking tungsten-chromium-manganese steels are also used.*

The metal used for the cores is usually an alloy steel, or the same steel as for the dies; high-speed steel cores are also favoured.

Heating the Dies

When die-castings are to be made it is usual to heat the dies to about 100° C. for the lower melting point alloys, and rather higher for the other alloys. Where rapid cooling of the metal after casting is required, in the case of fast production, the dies and cores are often made hollow for water-cooling; further, it is often necessary to lubricate the dies and cores with beeswax.

Die-casting Machines

Die-casting machines are of two types, namely, the compressed air and the plunger types; certain designs have been used, however, which employ centrifugal force. In the compressed air type the molten metal is enclosed in a reservoir connected by a pipe to the mould; air pressures up to 500 lb. per sq. in. are employed to force the molten metal into the moulds.

The plunger method, as its name implies, utilizes the principle of a moving plunger in the sealed molten metal vessel to force the metal into the mould; the plunger may be operated either by hand or mechanically.

Alloys for Die-castings

Hitherto, as mentioned previously, the die-casting process has been of limited application owing, principally, to the low strength properties of the alloys employed. It was found that the sharpest and most accurate die-castings were those from the zinc, lead, and tin alloys having low tensile strengths and poor ductilities. Most of the die-castings made from these alloys were suitable for ornamental purposes or where light loads only were involved.

* Full particulars of die steels are given in Chapter VI, Volume I, of this work.

As a result of research into die-casting methods and materials it is now possible to produce die-castings in aluminium alloys up to 16/18 tons per sq. in. More recently R.R. alloy has successfully been applied to die-cast pistons. Further, it is now possible to make die-castings from certain of the bronzes, e.g. aluminium and silicon bronzes.

Another class of high tensile alloys for die-casting is one containing zinc for the greater part, together with additions of aluminium, copper, and magnesium. Tensile strengths up to 21 tons per sq. in. have been obtained from alloys of this class, notably "Mazak" zinc-base alloys.

The alloys employed for die-casting may be divided broadly into four principal classes as follows—

(1) Lead-base Alloys

These contain lead for the greater part together with tin, antimony, bismuth, or copper. They are low strength die-casting alloys, giving sharp impressions of the mould. Lead toys are gravity die-cast from such alloys; low strength bearings for machinery are also made therefrom. Lead-base alloys are tolerably free from corrosion under ordinary conditions.

These alloys have melting points of about 320° C.–340° C. The following are some typical die-casting lead alloy compositions—

TABLE 83
LEAD-BASE DIE-CASTING ALLOYS

Description	Composition (Percentage)		
	Lead	Antimony	Tin
Magnolia	80	15	5
Monotype	74	18	8
Linotype :	83	12	5
Railroad bearing alloy . . .	64	26	10
Electrotype	93	4	3
Ordinary bearing alloy . . .	87	7	6
Light bearing alloy . . .	80	10	10
Standard type metal . . .	59	15	26*
Non-corroding alloy . . .	91	7·5	1·5
Alloy for battery plates, fire extinguisher parts and lead weights .	90	10	0
Alloy for light thrust washers and lightly loaded bearings . .	83	17	0

* With 1 per cent of copper.

(2) Tin-base Alloys

These alloys, in addition to their tin content—which forms the greater proportion—contain copper, lead, and antimony; in some cases bismuth is included. Their strength is relatively low, but they possess very good antifriction properties, and are, therefore, employed for engine bearings.

They give sharp die-castings with very little contraction so that the minimum of machining or scraping—in the case of bearings—is required; for many purposes the accuracy obtained in the dies is so satisfactory that further machining is unnecessary.

The melting point of these alloys is about 340° C. to 360° C. The dies should be heated to 80° C. to 100° C. before pouring the metal.

Tin-base alloys are free from corrosion by water, oils, or weak alkaline or acid solutions.

The tin-base whitemetals and Babbitt metals described in Chapter VII are mostly suitable for die-casting purposes and in each particular application the most suitable composition can be selected from the information there given.

In general the die-casting tin-base alloys are harder and stronger than the lead-base ones, but are more costly. They possess low frictional coefficients.

The tin-base alloys can be readily soldered and electroplated.

With the adoption of lined crankshaft and big-end connecting rod bearings, including the thin whitemetal-lined steel shell bearings used on high-performance petrol engines, the separately die-cast tin-alloy bearings have been to a large extent replaced by the former types.

Tin-base die-castings, apart from their use as bearings, are used where low shrinkage on cooling is required for accuracy, i.e. for number wheels, small gears, odometer parts, etc. Tin alloys suitable for die-casting include also the better grades of pewter, i.e. with lower lead content.

(3) Zinc-base Alloys

These alloys constitute the most widely used of the die-casting metals, about three times the weight of all die-castings being made of zinc-base alloys.

Most of these alloys consist of zinc hardened with copper and tin or copper and aluminium. Initially, a certain amount of trouble was experienced with die-castings of the zinc-base class due to inter-granular corrosion. The castings which appeared to be sound at first distorted and increased in size when stored; in other instances they developed cracks in service and even broke into pieces.

These defects were subsequently shown to be due to the presence of certain impurities in the zinc alloys and it was found that if these were kept below a definite limit the troubles mentioned did not occur. The use of purer grades of zinc up to 99·9 per cent purity by electrolytic and vapour refluxing processes has now resulted in the production of sound and permanent die-castings in zinc-base alloys.

The principal impurities in these alloys are lead and cadmium, and these constituents are kept down below 0·003 per cent.

In the case of the copper-tin-zinc alloys it has been found that the presence of aluminium in excess of 0·5 per cent has a deleterious effect so that the latter metal must be kept below this percentage. With the copper-aluminium-zinc alloys the presence of tin in excess of 0·005 tends to cause failure by distortion, swelling, and cracking.

The compositions of some typical zinc-base alloys are given in Table 84, and the mechanical properties in Table 85.

TABLE 84
COMPOSITIONS OF TYPICAL ZINC-BASE ALLOYS

Alloy	Aluminium	Copper	Tin	Magnesium	Zinc
A	0·5 (max.)	3·5	6·5	—	Remainder
B	0·5 (max.)	5·5	8·0	—	Remainder
C	4·0	3·0	—	—	Remainder
Zamak No. 2	3·9–4·3	2·5–2·9	—	0·02–0·05	Remainder
Zamak No. 5	3·9–4·3	0·75–1·25	—	0·02–0·05	Remainder
Zamak No. 6	3·9–4·3	1·0–1·5	—	0·005 (max.)	Remainder
Mazak* No. 3	3·9–4·3	None	0·001	0·03–0·06	Remainder
Durak	4·1	1·0	—	0·03	Remainder

* Mazak No. 2 and No. 5 have similar compositions and properties to Zamak No. 2 and No. 5 respectively.

TABLE 85
PROPERTIES OF TYPICAL ZINC-BASE ALLOYS

Alloy	Specific Gravity	Melting Point °C.	Tensile Strength Tons per sq. in.	Brinell Hardness	Compressive Strength Tons per sq. in.	Shear Strength Tons per sq. in.
A	6·65	410	9·0	—	—	—
B	6·65	415	8–9·0	53	—	—
C	6·60	398	15·6–17·8	57	—	—
Zamak No. 2	6·75	394	21·0	83	41·5	20·4
Zamak No. 5	6·67	386	18·6	73	39·0	17·1
Zamak No. 6	6·72	389	17·7	71	41·0	17·0
Mazak* No. 3	6·60	381	18·0 with 4·7% elongation	83	—	—
Durak*	6·60	380·5	22·91 with 2·8% elongation	100	—	—

B.S. Zinc Alloys for Die-casting. The British Standards Institution has issued two specifications, as follows: *B.S.* 1003 *High Purity Zinc*, and *B.S.* 1004 *Zinc Alloys for Die-castings*. The former relates to the high purity zinc used in zinc alloys for die-castings and specifies the following maximum percentages of the other elements, namely, lead, 0·003; cadmium, 0·003; other impurities (excluding iron and copper), traces. Total impurities 0·01 per cent. Two zinc alloys, designated A and B, are specified. The former has 3·9 to 4·3 per cent of aluminium, with very small specified amounts of copper, iron, magnesium, lead, tin, and cadmium, the remainder being zinc. The latter alloy has 3·9 to 4·3 per cent of aluminium with 0·75 to 1·25 per cent copper (as against 0·03 per cent in alloy A). Steam, weight, shrinkage and mechanical tests are specified. The mechanical properties are given in Table 86.

TABLE 86

MECHANICAL PROPERTIES OF B.S. ZINC ALLOYS FOR
DIE-CASTINGS

Alloy	Ultimate tensile stress tons per sq. in.			Elongation per cent on 2 in. × ¼-in. dia.			Impact strength* ft./lb.			Hardness (Brinell No.)		
	A	A(s)†	B	A	A(s)†	B	A	A(s)†	B	A	A(s)†	B
Original values	18·5	16·7	23·4	3·7	4·7	3·3	32	35	34	74	63	89
After 12 months' normal ageing	17·9	17·3	20·8	7·9	7·6	5·5	44	40	40	65	68	78
After 10 days' dry ageing at 95° C.	15·7	15·3	17·7	9·3	7·8	5·4	33	36	6·2	64	59	70

* Un-notched Charpy test piece ¼ in. × ¼ in. section.
† A(s)—Stabilized at 100° C.

Mazak Alloys. In reference to the Zamak alloys these are produced by the New Jersey Zinc Company of America and are widely employed in that country. The Mazak alloys are similar in their properties and are marketed in this country by Messrs. Morris Ashby Ltd., London.

In addition to aluminium, copper and magnesium the Mazak alloys have very small proportions of iron, lead and cadmium, the sum of these latter elements not exceeding 0·081 per cent.

The copper-aluminium-zinc alloys are about the strongest ones and, owing to the aluminium content, the fluidity of the molten metal is improved so that sound castings with thin sections can be produced. It is often necessary to heat-treat such alloys by heating to about
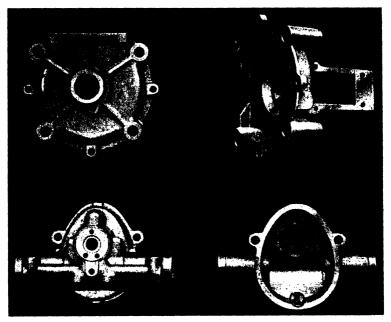
FIG. 133. GROUP OF MAZAK DIE-CASTINGS. THE UPPER ILLUSTRATIONS SHOW THE CRANKCASE UNITS OF A SMALL PETROL ENGINE

(Wolverhampton Die-casting Co., Ltd.)

280° C., followed by slow cooling to 240° C. and final cooling in air; this treatment accelerates any age-hardening effect.

The *thermal expansions* of Mazak alloys Nos. 2, 3 and 5 are $27 \cdot 7 \times 10^{-6}$, $27 \cdot 4 \times 10^{-6}$ and $27 \cdot 4 \times 10^{-6}$ per ° C. respectively.

The *solidification shrinkages* are $0 \cdot 15$, $0 \cdot 14$ and $0 \cdot 14$ in. per ft. respectively.

In regard to the *impact strengths* as tested on a Charpy machine of 40 ft.-lb. capacity with anvil gap of 40 mm. and using un-notched specimens, the respective values for the three alloys mentioned are $19 \cdot 00$, $20 \cdot 25$ and $17 \cdot 5$ ft.-lb.

Mazak alloys experience *ageing*, the metal being in a meta-stable state as soon as cast, since certain phase changes which normally

occur during slow cooling are suppressed. One phase change of small intensity is largely completed in five weeks; another occurs which requires several years for completion. In the case of the No. 3 Mazak alloy, after three years' ageing the tensile strength falls from 18·0 to 15·1 tons per sq. in., the percentage elongation increases from 4·7 to
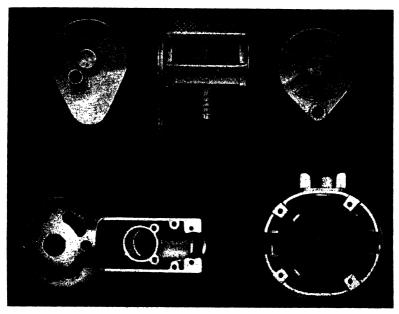
FIG. 134. GROUP OF MAZAK DIE-CASTINGS
(*Above*) Fishing-reel components. (*Below*) Electric hand-drill casings.
(*Wolverhampton Die-casting Co., Ltd.*)

6·1 and the Brinell hardness falls from 74 to 67. The No. 2 alloy shows a slight increase in tensile strength and hardness after three years, from 83 to 106, but the impact strength drops from 19 to 6 ft.-lb.

The changes due to ageing can be brought about by heating the castings at temperatures of 70° C. to 95° C., so that the phase changes of normal ageing are achieved in a few days. Improved Mazak alloys, employing higher casting pressures, now give higher mechanical test values, a typical alloy, known as Stabilized No. 3, having a tensile strength of 18·9 tons per sq. in. with 11·4 per cent elongation, Charpy impact strength of 34·9 ft.-lb. and Brinell hardness of 63.

The advantages of zinc-base alloys for die-castings are that they are relatively low in cost; are stronger than lead-base alloys; have easy

die-casting qualities at relatively low temperatures which permit the cheaper die steels to be employed; can be used with plunger-casting machines with readily obtained high pressures; are smooth and to close dimensional limits; can be cast in very thin sections; are readily machined when necessary; take any of the ordinary commercial finishes; and possess good surface corrosion resistance when high purity alloying elements are used.

In many instances, however, the zinc alloys show surface corrosion tendencies, especially in moist atmospheres and in contact with steam, so that in such cases surface protection coatings of chromium, nickel, etc., are necessary.

Among the numerous *commercial applications* of zinc-base die-castings the following may be mentioned, namely: Automobile radiator grilles, window and frame castings, heater casings, gramophone motor frames, parts of calculating machines, carburettor castings, washing machine components, refrigerator parts, instrument casings and parts, electric motor end covers and frames, petrol pump bodies for automobile fuel feed systems, tail and side lamp bodies, automobile bodywork fittings, e.g. door handles, window regulators and grips, domestic machine parts, typewriter frames, meter fittings, photographic accessories, canning machine parts, electric fan parts, etc.

One of the most important applications in automobiles is that of die-castings in strong zinc-base alloys of *radiator grilles*.* In this connection very thin sections can be cast, namely, down to about 0·020 in., and the smooth surfaces obtained require only a minimum amount of buffing in preparation for chromium plating. Complicated designs of such die-castings are readily produced and such castings often take the place of several assembled stampings, thus forming a one-piece structure which includes ribs, bosses, threaded elements and similar items. The employment of light sections for radiator grilles offsets to a large extent the greater density of the zinc-base alloy in comparison with steel stampings or pressings.

One disadvantage of many zinc-base thin section die-castings is that if accidentally broken they cannot be repaired satisfactorily.

In regard to the weights of radiator grilles, typical examples as used on the high-powered American cars, e.g. Cadillac, Buick and La Salle, weigh from 18 to 20 lb. In some instances these grilles are made in two sections, when the total weight with bolts, nuts and fixtures is rather higher.

Intercrystalline Corrosion. Zinc-base alloys are subject to this type

* See also "Die Cast Radiator Grilles," *Machinery Supplement*, 5th May, 1938.

of corrosion, which is due in some instances to stressed casting conditions and in others to impurities. Zinc-base die-castings have been shown to be more prone to intercrystalline corrosion when tin, lead and cadmium impurities each exceed a certain proportion; for this reason

FIG 135. AN INTRICATE DIE-CASTING IN MAZAK
ZINC-BASE ALLOY

the presence of these elements is restricted to very low proportions, as indicated with the British Standards alloys mentioned on page 276. As this corrosion occurs in the presence of moisture accelerated steam tests are usually employed to detect such tendencies.

Surface Finishes. In instances where good surface appearance is required on zinc-base die-castings—which normally possess a dense smooth skin—the castings can be painted, enamelled or varnished with suitable materials. For finishes requiring heat, e.g. stove enamels and synthetic resins, it is important to use a zinc alloy which does not

experience detrimental changes in mechanical properties or in dimensions by subsequent ageing at the stoving temperatures.

A special alloy suitable for stove enamelling is Mazak No. 3, which
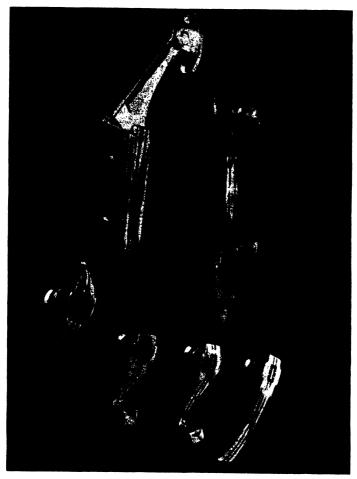
FIG. 136. TYPICAL EXAMPLES OF MOTOR-CAR DIE-CASTINGS
IN MAZAK ZINC-BASE ALLOY

can be heated to 150° C. to 218° C. without disadvantageous effects. The modern "low-bake synthetic" enamels require stoving at only 100° C. to 110° C., so that a wider range of alloys is available. Zinc-base castings can be electro-plated with nickel, chromium and silver, but special

precautions are necessary to ensure sound adherent coatings. These alloys can also be given copper, bronze, and brass finishes.

(4) Aluminium-base Alloys

After the zinc-base alloys these are the most widely employed for die-casting purposes. The use of aluminium alloys for these applications enables light high-strength castings to be produced to within
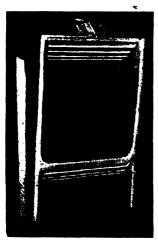
FIG. 137.   ALUMINIUM ALLOY (NA.226) GRAVITY DIE-CASTING BEFORE TEST
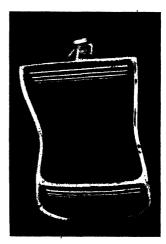
FIG. 138.   ALUMINIUM ALLOY (NA.226) DIE-CASTING AFTER TEST

fine dimensional limits. Such castings are permanent in shape and can be used over a much greater temperature range than the lead- or zinc-base ones. They possess excellent thermal and electrical conductivities also.

Die-castings can be made in quantities at a much lower cost per unit than sand-castings. Thin as well as thick sections may be cast.

Aluminium-base die-castings are smoother in appearance than sand-castings and the metal is denser. They can be produced so accurately that machining allowances and finishing costs are considerably less than for the best sand-castings.

The fact that metal dies or moulds are employed indicates more rapid cooling of the alloy with increased density of the resultant casting. The tensile strengths and hardnesses of die-castings are invariably higher than for sand-castings of the same alloy. Further, there is a notable absence of porosity and dross inclusions—in other

words, the castings are uniformly more sound. A further effect of the more rapid cooling is that of grain refinement throughout the mass of the metal; the increased hardness is due to this.

Alloys Used. There is now a fairly wide range of aluminium alloys available for die-casting purposes. Typical instances of these are the 8 and 12 per cent copper-aluminium alloys, aluminium-copper-silicon alloys, with or without the addition of small amounts of nickel, Y-alloy, R.R.53, R.R.53C, Hiduminium 23, Hiduminium 40 and 42, Birmal and other commercial alloys. Certain B.S.I. standard alloys, such as the aluminium-copper-tin L.11, aluminium-copper-zinc 6B, aluminium-copper L.8 and the aluminium-copper-zinc 2L.5, are also suitable for die-castings.

Another alloy having high strength properties is the NA.226,* which is made to conform to the D.T.D.361, D.T.D.304 and D.T.D.298 Specifications, giving tensile strengths (chill-cast and heat-treated) of 27·0, 25·0 and 19·0 tons per sq. in. respectively. This alloy contains from 4 to 5 per cent copper; 0·9 per cent (max.) silicon; 0·7 per cent (max.) iron; 0·25 per cent (max.) titanium; less than 0·2 per cent impurities; and the rest aluminium.

A typical American alloy forming one of the Alcoa range contains 14 per cent copper, 2 per cent silicon and the rest aluminium. It has a tensile strength of 16 tons per sq. in., with 1 per cent elongation and Brinell hardness of 95. The specific gravity is 2·98. The melting point (liquidus temperature) is 600° C. Another Alcoa alloy of the nickel-content class contains 4 per cent copper, 1·75 per cent silicon and 4 per cent of nickel. The tensile strength is 13·9 tons per sq. in. with 1·5 per cent elongation. The Brinell hardness is 80 and specific gravity 2·87. The melting point (liquidus temperature) is 629° C.

An example of a high-silicon content aluminium-base die-casting metal is the A.S.T.M. No. 5, having 12 per cent silicon and 88 per cent aluminium. This alloy possesses good fluidity and gives sharp mould impressions. It has a tensile strength of 14·7 tons per sq. in. with 1·5 per cent elongation.

From these considerations it will be seen that the aluminium is strengthened by suitable additions of other elements, notably copper, nickel and silicon. For pressure casting the amount of zinc must be kept low, as otherwise there would be a tendency to *red-shortness*; it should not exceed about 1·5 per cent as a general rule.

Effect of Silicon. The difficulty previously experienced in connection with somewhat excessive shrinkage of the aluminium alloys has been overcome by the inclusion of silicon, which not only reduces this

* Northern Aluminium Co. Ltd.

TABLE 87

Die-casting Aluminium Alloys

Designation			Minimum Mechanical Properties			Heat-treatment
Alloy	Specification	Form	0·1% Proof Stress Tons per sq. in.	Ultimate Tensile Stress Tons per sq. in.	Elonga-tion, per cent on 2 in.	
NA.226 . .	D.T.D.361 . .	C S	22·5 20	26 21	4 1	Full
Ceralumin C . NA.211 . .	D.T.D.225 . .	C S	20 17·5	23·5 18	— —	Full
R.R.53C .	D.T.D.309 . .	C S	19 18	22 19	— —	Full
R.R.53 . .	D.T.D.131A . .	C S	19 15·5	20 16	— —	Full
NA.161 . . Alpax Gamma	D.T.D.245 . .	C S	16 13	19 15·5	— —	Full
NA.222 . .	D.T.D.269 . .	C S	14 13	19 18	— —	Full
Y-Alloy . .	B.S.S. L.35 . .	C S	14 13	18 14	2 —	Full
Ceralumin D . NA.211 . .	D.T.D.250 . .	C S	13 11·5	20 14	5 —	Full
NA.125 . .	D.T.D.272 . .	C S	10 8	13 11	— 2	Solution
NA.161/A3 . Alpax Beta .	D.T.D.240 . .	C S	8·5 6	15 11	3 1·5	Ageing
NA.218 . . Y-Alloy . .	B.S.S.2. L.24 . .	C S	8·5 8·5	12 10	— —	None
Ceralumin B . NA.111 . .	D.T.D.287 . .	C S	8 7·5	12·5 10	4 2	Ageing
R.R.50 . .	D.T.D.133B . .	C S	8 7·5	12·5 11	4 2·5	Ageing
Birmasil Special NA.158 . .	D.T.D.264 . .	C S	6 4·5	16 12	3 2	None
Birmabright .	D.T.D.165 . .	C S	5 5	11 9	5 3	None
NA.160 . . Alpax . .	B.S.S.L33 . .	C S	4·5 3·5	13 10·5	8 5	None
M.V.C. . .	D.T.D.231 . .	C S	4·5 3	12 10	7 5	None

C = Chill-cast.   S = Sand-cast.

[Northern Aluminium Co.]

shrinkage but increases fluidity and avoids any cracking tendency; moreover, it improves both the malleability and corrosion resistance appreciably. Aluminium-silicon alloys are free from hot-shortness, but if the silicon content is high there is a tendency for the molten metal to attack the iron of the melting pots and submerged goosenecks. The silicon imparts a bluish tinge to the aluminium.

The ductility of the high silicon content (12 to 14 per cent) aluminium alloys is improved and the grain structure refined—but at the expense of a loss in tensile strength—by annealing the die-castings for one or two hours at a temperature of 400° C., followed by slow cooling. The hardness is also reduced by about 30 per cent by this process.

Aluminium alloys have a solvent action on iron and it has been shown by analyses of typical die-castings that from 1 to 3 per cent of iron is often present. One effect of this is to raise the melting point of the alloy. Prolonged contact of the molten alloy with iron melting pots may affect the fluidity of the alloy and result in surface defects on the castings.

Economy of Die-castings

Apart from the fact that aluminium-base die-castings have a smoother and much cleaner appearance than sand-castings and are from 10 to 20 per cent stronger in tensile strength and hardness, they can be produced more cheaply, provided that a sufficiently large number of castings is produced, in order to offset the relatively high cost of the dies and machines employed.

In the case of gravity die-castings the economic minimum usually lies between 1000 and 3000, the former value being for the more complicated castings and the latter for the relatively simple ones. For pressure die-castings, however, where the costs of the machine and dies are greater, the minimum quantities that can be produced economically are somewhat greater than for gravity castings.

In connection with *the life of the dies* used for pressure casting of aluminium-base alloys, when correctly designed and of the most suitable alloy die steel, these dies are usually good for 20,000 to 100,000 castings, according to the size and design, type of alloy used, etc. The *maximum weights of castings* of plain section that are made at present by the pressure method are about 15 to 18 lb., and the dimensions 20 × 10 × 36 in. The sectional thicknesses are limited to a minimum of about $\frac{1}{16}$ in., and the usual tolerances are within $\pm$ 0·001 in. (in special instances) to 0·002 in. (normal values).

An interesting comparison between the cost and output in the case

of pressure die-castings in aluminium alloys* is given in Fig. 139, which shows how the cost per 100 castings diminishes with the number of castings produced. The hatched area below the horizontal line denotes material and production costs per 100 castings, excluding the cost of the dies. The hatched area above the horizontal line represents the proportionate die costs per 100 castings.

An interesting example of the saving effected in the application of die-castings is that of the Leyland commercial vehicle gear-box which
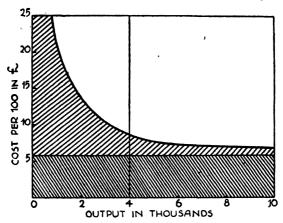
FIG. 139. RELATION BETWEEN DIE COST AND OUTPUT OF PRESSURE DIE-CASTINGS IN ALUMINIUM ALLOYS

was made of an aluminium alloy containing 7·5 per cent copper and 3·5 per cent silicon. The finished casting weighed 52 lb. When made as a sand-casting the time of production was 225 min., but for the die-casting this time was only 12 min. The contraction allowance was 0·008 per inch. The weight of the die—which contained twenty-eight working parts—was about a ton. The pouring temperature was 750° C., the mould being preheated to 400° C. The gravity die-casting method was employed in this example.

Pressure and Gravity Die-castings

Pressure castings require the use of more expensive dies and involve higher setting-up costs. They necessitate the use of plant which will produce injection pressures of a high order, namely, up to about 5000 lb. per sq. in., although in special cases higher injection pressures are employed. In the case of low pressure or hand-operated machines pressures as low as 80 to 100 lb. per sq. in. are often used. The dies

and their supports must therefore be designed sufficiently rigid to withstand these pressures without any tendency for the dies to open.

In general the pressure method is considered to give slightly denser castings, with greater accuracy for the finished parts than by the gravity process. Thinner sections (down to about $\frac{1}{32}$ in.) can be cast by the pressure process. The speed of production by the pressure method is from four to five times greater than that of the gravity one and the parts as removed from the plant are usually in completed form, requiring the minimum of machining other than sizing to precision limits by surfacing methods such as reaming, honing, grinding, etc. As the castings leave the dies they have a rather better surface finish than by the gravity method.

The advantages of gravity die-castings are that they are usually cheaper to produce per unit part, are but little inferior in density and finish and can be made for casting designs involving complicated undercut portions, such as those of petrol-engine pistons and crankcases. The pressure method has its limitations for such purposes, since the complicated dies or intricate built-up core units would prove excessive in cost and operation time.

A further advantage of the gravity process is that it can be used with a much wider range of aluminium alloy compositions than the pressure process, with which only a restricted range is possible.

A typical application of the gravity die-casting method is illustrated in Fig. 140,* the particular design being for an Austin small engine piston. When cast in chill moulds with steel cores this can be produced at the rate of fifty per hour, as compared with ten per hour for the sand mould cast pistons. The core is of a somewhat intricate shape, but by making it in steel in several pieces it can readily be assembled and also withdrawn. As soon as the metal in the runner is set the gudgeon pin cores are eased out and the centre wedge removed. The latches are then thrown back and the two cores forming the contour of the inside of the piston are taken out; finally, the die is opened and the castings removed. It will be seen from the illustration that the runner is of gooseneck form in order to control the rate of flow of the metal.

Increase in size or intricacy of the casting to be made reduces the advantage of the die-casting method until the point is reached where the sand-casting method becomes preferable.

Cold shuts in die-castings are skin formations on thin sections by

* *Gravity Die-castings in Aluminium Alloys,* Northern Aluminium Co. publication.

chilling and occur when the continuity of liquid metal in the mould
is broken, owing to the solidification of one or more streams of metal
before the mould is completely filled. For this reason thicker sections
should not be fed through thinner ones and adequate radii should be
left at corners wherever possible.

The *high shrinkage of aluminium alloys* on solidification necessitates
the provision for a ready flow of molten metal in order to avoid

FIG. 140. GRAVITY DIE-CAST PISTON FOR AUSTIN
AUTOMOBILE ENGINE

shrinkage cavities and "*draws.*" These defects are usually safeguarded
against by placing risers above heavy sections to ensure that fresh
metal shall replace that drawn away by adjacent parts which solidify
more rapidly. In instances where thin sections adjoin thick ones the
differential shrinkage effect is sometimes such as to cause *cracking*, so
that careful design of the casting and metal feeding methods is neces-
sary for its avoidance.

Applications of Aluminium Die-castings. There is a wide range of
parts made by die-casting methods in mass-produced engines,
machinery, instruments, domestic and other plant.

In automobile and aircraft engines, typical applications include
pistons, crankcases, carburettor castings, dynamo and starting motor
frames and other parts, magneto casings and end covers, oil sumps,
sparking-plug fins and radio shield parts, high strength levers and
brackets, etc. The undercarriages (retractable) of aircraft utilize

several high strength aluminium die-castings. Other aircraft applications include pilots' control levers, impellers for superchargers, brackets, tubular fittings, etc. Brake shoes for automobiles, cooling fans. clutch components, covers, levers, brackets and similar items requiring high strength for low weight are among some of the other applications of die-castings.

Aluminium die-castings are also used for domestic articles such as vacuum-cleaner motor and nozzle units, refrigerator radiator cylinders, spouts for tea and coffee pots, juice-extractors, washing machine agitators and cover frames, food mixers, wringer parts, etc.

Typewriter frames, camera bodies, parts of adding machines, meat slicers, vending machine components, and various office machines are also made by the aluminium die-casting method.

Certain elements of machine tools produced in quantity made by this method include gear-box castings and covers, pulleys, hand wheels, chain cases, etc. Portable electric and compressed air tools also employ die-cast components.

In the electrical industry there is also a wide field of application in connection with parts for dynamos, motors, instruments, telephone parts, meters, switchgear, traffic signal light hood units, etc.
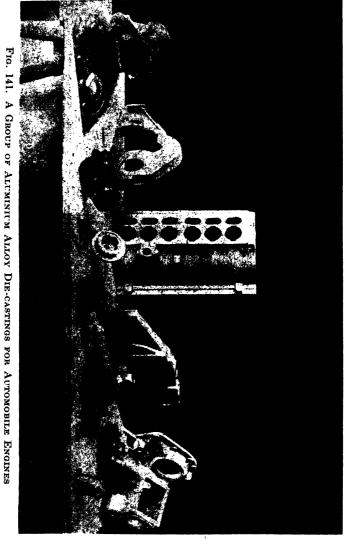
Aluminium alloys are melted in a furnace crucible and kept at about 10° C. above the melting point before pouring. The dies are heated to about 250° C. to 400° C. It is necessary to lubricate them in order to facilitate the removal of the casting. For this purpose a mixture of lard, oil, beeswax, and graphite is recommended.

A facing of French chalk is usually given to the dies.

Magnesium-base Alloys

Magnesium-base alloys of certain compositions can be die-cast satisfactorily although special methods have to be employed on account of the inflammable nature of these alloys. More recently a new type of furnace has been used for charging the metal in small quantities for each casting or "shot" into the machine whilst keeping the bulk of the metal in a neutral atmosphere. It has thus been possible to cast at 600° C. to 650° C. with the pressure casting method, using pressures up to nearly 6000 lb. per sq. in.; the die-castings produced have tensile strengths up to 15 tons per sq. in.

Owing to the lightness of magnesium alloys, combined with good strength properties, the sections of castings can be made thicker than those of aluminium alloys of equal stiffness so that the design, from the point of die-casting, is to some extent simplified and very thin sections which would cause casting difficulties are thus avoided.

Fig. 141. A Group of Aluminium Alloy Die-castings for Automobile Engines

Die-castings now made in the Elektron and Dowmetal magnesium alloys are becoming more widely used for aircraft purposes where high strength-to-weight ratio is required. To some extent these castings are replacing those of aluminium alloys.

Typical applications include bell-cranks, control brackets, tail wheel forks, retractable undercarriage fittings, window frames, housings, engine covers, brackets and certain other lightly stressed fittings, air-intake scoops, aileron hinge brackets, airframe fittings, etc. In the case of large radial engines supercharger impellers and crankcase sections, covers and accessory housings have been made.

In regard to the alloys employed for die-casting, in addition to certain of those given in Chapter IV, there is a range of Dowmetals, used for pressure castings in the United States, particulars of which are given in Table 88.

The die-casting qualities of magnesium alloys depend upon the actual compositions, those with the higher aluminium content being the more easy to cast. An improvement in the casting results can, however, be obtained in the case of the more difficult alloys by employing higher casting pressures.

TABLE 88

DIE-CASTING MAGNESIUM ALLOYS (DOWMETAL)

Dow-metal	Composition (Percentage)			Tensile Strength Tons per sq. in.	Elonga-tion on 2 in. per cent	Impact Value Charpy Ft.-lb.
	Alumi-nium	Mangan-ese	Magne-sium			
M	0	1·5	98·5	10·7–11·7	7–12	4–7
F	4	0·3	95·7	11·7–13·8	7–10	6–10
E	6	0·3	93·7	11·2–14·3	4–7	3–6
A	8	0·2	91·8	12·9–14·3	2–6	2–4
G	10	0·1	89·9	12·9–14·7	1·3	1–2
B	12	0·1	87·9	12·9–14·3	0·5–1·5	0·3–1·0

In connection with the alloys given in Table 88 Dowmetal G gives the best combination of casting and physical properties, whilst Dowmetal M possesses the best corrosion resistance. Another magnesium alloy having 10 per cent aluminium and 0·2 per cent manganese is also used on account of its satisfactory die-casting properties. It has a tensile strength of 12·5 to 13·5 tons per sq. in. with 1 to 2 per cent elongation and a Brinell hardness of 55 to 60; the specific gravity is 1·81.

Copper-base Alloys

Most of the brasses and bronzes described in Chapter V can be die-cast satisfactorily, although the relatively high melting points of these alloys introduce complications in regard to the length of useful life of the dies employed, since the shorter period before which the dies have to be discarded affects the economical production of the castings. For this reason the more simple parts in these alloys can usually be made at appreciably lower cost by the hot stamping process. Further, the machines used for die-casting copper alloys are of different design from those for most other alloys, so that it is not usually possible to utilize the latter type. Some of the machines employed for copper base die-castings operate upon the principle of ladling the molten metal from a melting pot into a cylindrical member from which a hydraulic ram forces it in the plastic condition into the dies, as distinct from using the molten metal for this purpose.

In regard to the life of the alloy steel dies it is usually possible to obtain about 30,000 to 50,000 castings only per set of dies. The dimensional limits possible with copper-base alloy die-castings are somewhat less than those of the other die-casting alloys previously considered, but they are usually such that considerably less final machining is necessary than for sand or forged parts of similar design. It is possible also to die-cast brass to sections as thin as $\frac{1}{16}$ inch.

The alloys most used for die-castings include the hot stamping brasses, extrudable brasses, yellow brasses, nickel silvers and certain bronzes, particulars of which are given in Chapter V. In order to minimize the cost of the dies and therefore to reduce the cost per casting, the alloys having the lower melting points are preferred in cases where maximum strength and similar mechanical properties are not the ruling factors.

Bronze alloys of 88 per cent copper and 8 to 10 per cent tin with small proportions of lead and zinc can also be die-cast satisfactorily. In regard to season cracking defects these are notably absent in die-cast copper alloys, but occasionally *blistering* due to a very small degree of porosity in the metal of die-castings is experienced.

The applications of die-castings in copper-base alloys include those fields in which relatively high strength properties combined with marked resistance to corrosion by impure atmospheres and certain liquids are required. For these reasons they are employed for components of plant used for handling liquids and gases, for marine purposes, domestic hardware, gears for small machines, meters, instruments, etc., nozzles, unions, elbow-fittings, tap and cock fittings, special

bearings, impellers and pump parts for liquids, bolts, nuts, caps and covers, etc.

In connection with the die-casting methods used, the gravity one is generally employed for parts in aluminium bronze, high tensile brass and nickel brasses and silvers. The pressure method can, however, be employed, but the life of the dies is shorter and their initial cost higher.

Aluminium Bronzes

The aluminium bronzes lend themselves admirably to the gravity die-casting process. These are employed commercially for castings of intricate shape. The alloys used range from 90 per cent copper, 10 per cent aluminium to those containing iron, manganese, and nickel in varying proportions, and the series extends to the aluminium brasses, or those containing copper and zinc as the main constituents with aluminium as an extra one. The brasses are not free from difficulties in the casting operations owing to the formation of zinc oxide.

The results of some tests* carried out on aluminium bronze alloys suitable for die-casting are given in Table 89.

TABLE 89

ALUMINIUM BRONZE DIE-CASTING ALLOYS

Chemical Composition (Percentages)			Mechanical Properties		
Al	Fe	Cu	Tensile Strength Tons per sq. in.	Elongation per cent	Proof Stress Tons per sq. in.
9·7	—	90·3	29·9	14	12·3
10·4	- -	89·6	33·6	23	10·2
8·6	1·4	90·0	31·7	42	11·1
10·5	2·2	87·3	35·6	13	13·0
10·2	2·8	87·0	39·4	12	14·1

Table 90, p. 295, gives particulars of some typical die-casting aluminium bronzes.

Aluminium bronzes cast well, one set of dies being capable of producing at least 15,000 to 20,000 castings.

* "Die Castings," F. Fry, *Proc. Inst. Mech. Engrs.* (September, 1930).

Iron-base Alloys

In concluding this chapter, reference should be made to the fact that it is now possible to produce grey iron castings in metal moulds;

FIG. 142. ALUMINIUM BRONZE DIE-CASTINGS OF 33/35 TONS PER SQ. IN. TENSILE STRENGTH

(*Messrs. Sagar Richards, Ltd.*)

a particular example is the Szekeley process for casting iron in metal moulds lined with a mixture of French chalk and paraffin.

The Holley Carburettor Co., of America, have used 'die-cast, cast iron for carburettor bodies for the Ford Co. The castings vary from ⅛ in. to ½ in. in thickness, and up to 10,000 can be produced from one

set of dies. The dies are faced with a thin mixture of water, fireclay, and waterglass baked with a thickness of $\frac{1}{64}$ in. and smoked.

TABLE 90

DIE-CASTING ALUMINIUM BRONZES (Russell)

Al	Fe	Pb	Remarks
10	---	- -	E.L.* 8 tons T.S.†.34–36, Elong. 19·5%, R. of A.‡ 23%.
9	3·5	—	Less liable to self-anneal than the above.
11	—		Gear bronze.
10	---	1	Gear bronze T.S. 36–37, Elong. 15%.
5–11	Up to 3·0	—	General purposes.

* E.L.—Elastic Limit.   † T.S.—Tensile Strength.
‡ R. of A.—Reduction of area.

Note. In the above table, the remainder is copper in each case.

SOME OTHER ENGINEERING ALLOYS

Solders

THESE are alloys of certain metals having relatively low melting points in relation to those of the base-metals to be united, so that they can be applied to the latter without risk of melting them. The solders employed commercially, when properly applied to the joints in the metal parts to be united, not only fill the spaces between the parts, but unite with the surface layers. Thus, in the case of two metal parts united with lead-tin solder, if the surfaces are properly cleaned before and fluxed during the soldering operation, the solder occupies all of the space between the parts, whilst at the surface layers the tin forms an alloy with the metals of the parts; in effect the tin dissolves some of the surface metal and in doing so penetrates into it. This alloying process has the further advantage of requiring only a relatively low temperature, namely, below 300° C., for lead-tin solders.

The solders used in engineering work can be divided into two groups, as follows: (1) *The Soft Solders*, and (2) *The Hard Solders*. The former have low melting points and are composed chiefly of lead and tin—in some instances with small additions of antimony. The latter class includes the *Silver Solders* and *Brazing Metals*, which have higher melting points and give stronger joints.

It should be pointed out that although the term "hard soldering" is widely used to include both silver soldering and brazing, the latter process is often used to define the method of uniting two metals with a film of brass or spelter.

These two groups of solders are used for uniting steel, cast iron, copper, brasses, bronzes and certain other metals and alloys such as lead, zinc, whitemetals, pewters, etc.; in this connection each metal or alloy requires its own particular composition of solder, although certain of the lead-tin solders will unite steel, copper, brass, bronze, or whitemetal equally well. None of the usual hard or soft solders can be employed for uniting aluminium or magnesium or the alloys of these metals.

The Lead-tin Solders

The simple soft solders are alloys of lead and tin, the exact composition used depending upon the purpose for which the solder is to be

employed. Lead and tin will alloy in any proportions giving a range of alloys from just below 100 per cent lead on the one hand to just below 100 per cent tin on the other.

Fig. 143 shows the approximate equilibrium or freezing point diagram for lead and tin. The line *AEB* represents the temperature conditions for the various alloys at which the liquid alloy when cooled
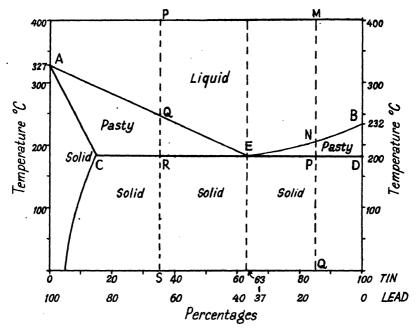
Fig. 143. Equilibrium Diagram for Lead and Tin

slowly begins to enter the "pasty" state. The line *CED* which passes horizontally through 183° C. on the temperature scale corresponds with the solidification of the alloy and is the temperature at which the *eutectic* consisting of 63 per cent of tin and 37 per cent of lead forms direct from the liquid (or molten) condition into the solid state without passing through the pasty condition. This alloy has the lowest melting point of all the lead-tin ones. Those with the higher melting points contain the greater percentages of lead; thus as the percentage of the latter metal is increased the melting point increases along the line *EA*, until the melting point of lead, at 327° C., is approached. Alloys containing greater proportions of tin than 63 per cent have melting points between 183° C. and 232° C. (the melting point of tin).

It is interesting to consider the physical states of alloys during the cooling process for tin compositions of less than that of the eutectic denoted by E in Fig. 143. Thus, for the alloy containing 35 per cent of tin and 65 per cent lead, denoted by the ordinate $PQRS$, as the molten alloy is cooled from the temperature corresponding to P, namely, 400° C., it eventually drops to the temperature denoted by the point Q, namely, 245° C., below which it enters the pasty region of the equilibrium diagram when crystals of lead begin to form and, with further reduction of temperature, to grow with consequent increase in the pastiness of the alloy. The residual liquid portion corresponds to the composition of the eutectic, namely, 63 per cent tin and 37 per cent lead. When the temperature eventually falls to the value denoted by R, the alloy passes from the thick pasty to the solid condition; the structure of this solidified alloy consists of lead crystals in the eutectic of lead and tin.

For alloys containing more than 63 per cent of tin the pasty condition is denoted in Fig. 143 by the area enclosed by EBD; the constitution of the partly solidified alloy consists of tin crystals in the liquid lead-tin eutectic, and the solid alloy (below 183° C.) therefore consists of tin crystals in lead-tin eutectic. The ordinate $MNPQ$ represents the cooling sequence of the 85 per cent tin alloy which is "pasty" along NP and solidifies at P.

Physical and Strength Properties. The physical and mechanical properties of lead-tin alloys are given in convenient form in Table 91.*

Some Ordinary Solders

Among the lead-tin solders that have been in use over a long period are those known respectively as Plumbers' Solder and Tinman's or Blowpipe Solder.

Plumbers' Solder, which is widely used in ordinary soft soldering practice, consists of 66·6 per cent lead and 33·3 per cent tin (or 2 parts lead and 1 part tin). It has a wide plastic condition range from the melting point of 250° C. down to the solidification point of 183° C., and it gives a tensile strength of about 2·7 tons per sq. in. and shear strength of about 2 tons per sq. in.

Tinman's Solder has a composition of 33·3 per cent lead and 66·6 per cent tin (or 1 part lead to 2 parts tin). It very nearly coincides with the composition of the eutectic with solidifying point of 183° C. and is suitable for blowpipe use since it has no appreciable intermediate pasty condition.

Tin Solder is the name that is sometimes given to the 50/50 lead-tin

* Publication No. 93, International Tin Research and Development Council.

TABLE 91

PROPERTIES OF LEAD-TIN ALLOYS

Properties	Tin, per cent (remainder Lead)					
	100	63	50	40	30	0
Temperature of complete liquefaction	232° C. (450° F.)	183° C. (359° F.)	212° C. (414° F.)	238° C. (460° F.)	257° C. (496° F.)	327° C. (620° F.)
Temperature of complete solidification	232° C. (450° F.)	183° C. (359° F.)	183° C. (359° F.)	183° C. (359° F.)	183° C. (359° F.)	327° C. (620° F.)
Freezing range	0° C. (0° F.)	0° C. (0° F.)	29° C. (55° F.)	55° C. (101° F.)	74° C. (137° F.)	0° C. (0° F.)
Specific gravity	7·31	8·42	8·91	9·34	9·78	11·34
Tensile strength* (tons per sq. in.)	0·94	3·35	2·75	2·75	2·66	0·89
Elongation (per cent on 4 in.)	55	32	43	35	26	39
Shear strength* (tons per sq. in.)	1·28	2·78	2·56	2·22	2·06	0·90
Izod impact strength (ft.-lb.)	14·2	14·8	15·5	14·1	11·5	5·6
Brinell hardness	4·6	13·9	12·0	11·3	8·7	4·1
Electrical conductivity (per cent of conductivity of copper)	13·9	11·9	11·0	10·2	9·5	7·91

* Values obtained by fairly rapid rates of loading.

solder which melts at 212° C. and has a tensile strength of about 2·75 tons per sq. in., and a shear strength only slightly less, namely, 2·56 tons per sq. in. It is rather stronger, harder and more ductile than Plumbers' Solder.

Effect of Antimony in Lead-tin Solders

The addition of small proportions of antimony to certain lead-tin solders increases the tensile, shear and compressive strengths as well as the hardness. The maximum percentage of antimony that can be added advantageously should not exceed 6, since above this amount hard crystals of tin-antimony compound are formed which tend to make the solder brittle and also to reduce its surface alloying or adhesive properties. If 1 per cent of antimony is added to a lead-tin alloy the amount of tin may be reduced by 2 per cent to preserve the same proportion of eutectic. Similarly, for every 1 per cent of antimony added there must be a simultaneous addition of 1 per cent of lead. The lead-tin-antimony eutectic has a slightly higher melting point, namely, 3° C. higher than the lead-tin eutectic. When a small proportion of antimony is added to plumbers' solder the plastic range is sensibly the same.

At the tin end of the equilibrium diagram 7 per cent of antimony increases the freezing point by 11° C., but over the ordinary solder alloy range the usual additions of antimony do not increase the freezing point to any appreciable extent.

A typical antimony solder contains 45 per cent tin, 52·5 per cent lead, and 2½ per cent antimony. It is equivalent to the 50/50 lead-tin alloy, but the tensile strength is 3·6 as compared with 2·75 tons per sq. in. for the latter alloy; it is also appreciably harder.

It should again be emphasized that whilst the lead in the solder has no power to dissolve any antimony the tin will carry up to about 6 per cent of antimony without formation of brittle tin-antimony cubic crystals.

It has been shown by Nightingale* that antimony in lead-tin solders causes a slower alloying action on brass and copper, but gives stronger joints, though in the case of mild steel the joints made were less strong than those obtained with antimony-free solder; when more than 55 per cent of lead was present the antimony had a detrimental effect. The strongest joints were found to be those made with a solder consisting of pure tin with 6 per cent antimony, but no lead.

Most of the British Standard Soft Solders (Spec. No. 219, 1932)

* *Tin Solders*, S. J. Nightingale, British Non-Ferrous Metals Research Association, London.

allow for maximum percentages of antimony up to 3·0 and in three instances definite minimum percentages up to 2·5 per cent are specified.

Solders for Elevated Temperatures

The lead-tin solders, whilst sufficiently strong in tension and shear at normal temperatures for most purposes, show a somewhat marked falling off in strength with temperature rise. 'Thus in the case of a solder having equal proportions of lead and tin the tensile strength falls to one-half its normal air temperature value at 150° C., i.e. at 33° C. below its solidification point; for this reason no stress should be applied to soldered joints until they have cooled right down.

In instances where stressed soft soldered joints are exposed to temperatures appreciably above normal air values the high tin content solders should be used. Thus a solder containing 95 per cent tin and 5 per cent antimony has a tensile strength of 2·81 tons per sq. in. and melts at 244° C., whereas pure tin has a tensile strength of only 0·94 ton per sq. in. and melts at 232° C.

The *antimonial-tin solder* mentioned is employed in electrical and other work where the temperature is likely to reach or exceed the boiling point of water; this solder possesses a good electrical conductivity. It is used also in refrigerator condenser systems owing to its high strength and corrosion resistance properties.

The *cadmium-zinc solder* mentioned later is used for aircraft radiator construction on account of its good properties at temperatures appreciably above the boiling point of water.

Lead-silver alloys are also used for the same reason. A typical alloy is Fry's L.S.I, which melts at 305° C. and has hardnesses at 15° C., 100° C. and 180° C. of 7·1, 5·35 and 3·0. This solder is suitable for use at temperatures of 100° C. to 150° C. as it has good tensile and shear strengths combined with superior corrosion resistance to the lead-tin solders. It is particularly suited to electrical purposes as it possesses an appreciably higher electrical conductivity than ordinary soft solders.

An investigation made in the U.S.A.[*] into the possibility of substituting silver for tin in lead-tin solders, in instances where tin supplies were needed for armament industry purposes, indicated that a large saving in tin could be effected by using a 2·5 per cent silver-lead solder in place of the 50/50 lead-tin one. It was stated that not only was this new solder cheaper, but equally satisfactory joints could be obtained. This solder has been used in several industrial applications, including that of automatic can-making machines.

* *Automotive Industries*, 15th August, 1941.

British Standard Soft Solders

Ten different grades of soft solders are included in the Specification referred to on page 300. Their compositions and recommended applications are given in Table 92.

TABLE 92

COMPOSITIONS AND APPLICATIONS OF B.S.S. SOFT SOLDERS

B.S.S. Grade	Tin per cent		Antimony per cent		Total Impurities per cent	Lead	Recommended Applications, etc.
	Min.	Max.	Min.	Max.			
A	64·0	66·0	—	1·0	0·32	Rem.	Close to eutectic. Low melting point. For high strength thin joints, e.g. steel tubes.
B	49·0	51·0	2·5	3·0	0·32	Rem.	Tinman's solder for use with soldering bit. For tinsmiths' and coppersmiths' work.
C	39·0	41·0	2·0	2·40	0·32	Rem.	For hand soldering with soldering bit. General work. Slow setting solder.
D	29·0	31·0	1·0	1·70	0·32	Rem.	Plumbers' solder for lead pipe, sheets, wiped joints, etc.
E	94·5	95·5	—	0·50	0·25	Rem.	Special electrical purposes where high strength, conductivity and ductility are required.
F	49·0	51·0	—	0·50	0·32	Rem.	General electrical purposes. Suitable for zinc and galvanized iron, dipping baths, machine soldering, etc.
G	41·0	43·0	—	0·40	0·32	Rem.	For dipping baths, zinc and galvanized work. Tinned electrical joints.
H	34·0	36·0	—	0·30	0·32	Rem.	More liquid than Grade D. Used for wiped electrical cable joints.
J	29·0	31·0	—	0·30	0·32	Rem.	For dipping baths. Tinning caps and liners. For lead, copper, brass and steel fittings. Resembles plumbers' solder.
K	59·0	61·0	—	0·30	0·32	Rem.	Special machine soldering. For sealing cans. Sets quickly like eutectic. Gives strong ductile joints.

Impurities in Soft Solders

It is usual to specify certain maximum allowable percentages of impurities in soft solders. In this connection *zinc* is probably the most harmful ingredient, its presence being indicated by sluggishness of the molten metal with irregular waves and lumps on the surface, and by a dull yellow-white colour; even in amounts of 0·001 per cent zinc will spoil the solder.

Aluminium is almost as harmful as zinc and must be absent from solder.

Arsenic tends to make the solder brittle and it should not be present in greater amount than 0·05 per cent. It dulls the surface and causes small white spots on the surface.

Copper gives rise to grittiness and makes the molten solder sluggish. It should not exceed 0·08 per cent.

Iron causes brittleness and grittiness and should not exceed 0·02 per cent; when present above this amount it tends to cause dark streaks and smears in the alloy.

Phosphorus tends to render the solder too liquid and should be absent in the composition of the latter.

Special Forms of Solder

For convenience of soldering, soft solder is supplied in the form of ingots for tinning and dipping baths, in sticks of about ¼ in. to ⅜ in. for hand soldering and in powder form for fine work. For electrical, instrument and other small work purposes the solder is often supplied in the form of small diameter tubes with the interior filled with flux such as resin; it is known as *Flux-cored Solder.*

Powdered solder is often sold mixed with flux in the form of a paste; usually glycerine or grease is used as a carrier for the flux and solder. A typical soldering paste contains powdered solder, ammonium chloride (sal ammoniac) and glycerine; the solder should have a high tin content.

Tinning powders, which render the soldering of dirty surfaces, hardened steel, cast iron, etc., much easier, contain equal weights of powdered ammonium chloride and finely powdered tin or high tin content solder. A proprietary self-fluxing tinning compound of this class which has found a wide range of applications is that known as *Soldo.*

Fluxes for Soft Soldering

The following is a list of the fluxes employed for preventing oxidation and removing dirt and scum from the surfaces of the metals mentioned.*

Lead to lead with plumbers' solder . .	Tallow
Lead to brass or gunmetal with plumbers' solder	Tallow
Lead to brass or gunmetal with tinsmith's solder	Tallow or resin
Tinning brass or gunmetal for soldering . .	Tallow or resin

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* *Notes on Soldering.* Publication No. 93. International Tin Research and Development Council.

Clean zinc, copper, brass, etc., for bit soldering .	Zinc chloride
Zinc, not cleaned	Dilute hydrochloric acid
Tinplate for bit soldering	Zinc chloride
Pewter and block tin	Olive or Gallipoli oil, tallow, etc.
Tinning copper bits	Ammonium chloride or zinc chloride
Stainless steel, nickel or Monel metal	Saturated zinc chloride in 50 per cent hydrochloric acid
Wrought iron	Zinc chloride
Cast iron	Zinc or ammonium chloride
Brass, gunmetal, or copper	Zinc chloride, resin, or ammonium chloride
Bronze	Zinc chloride or resin
Bismuth	Zinc chloride or resin
Terne plate	Zinc chloride

In connection with the selection and use of fluxes it is important, when corrosive fluxes such as zinc chloride, dilute hydrochloric acid and ammonium chloride are employed, to remove all traces of the flux from the surfaces of the metals joined, by scraping, wire-brushing and washing. For electrical work the resin solders are generally preferred since there is no corrosive effect with this flux. Tallow and certain non-acid oils also have a similar advantage.

In all soldering operations the metal surfaces must be free from dirt and grease before heating; a preliminary cleaning by filing, emery-papering or pickling in a dilute hydrochloric acid bath followed by washing in water is recommended for steel, copper, and brass.

Cast Iron Soldering

Cast iron is a somewhat difficult metal to solder owing to the free graphite content and non-metallic inclusions. The white cast irons are more easy to soft solder than the grey ones for this reason. The surfaces to be soldered are prepared by various alternative methods, one of the most successful of which is the application of hydrofluoric acid. The surface may be plated with copper by applying moistened copper sulphate to the clean grease-free surface; when thus plated the solder will usually adhere satisfactorily.

Surface decarburization is another method which, although complicated and expensive, gives good results.

Good grades of cast iron as used for automobile cylinders can be prepared for soft soldering by grinding or filing, and then pickling with a 15 to 25 per cent solution of hydrochloric acid, followed by washing in clean water. Zinc chloride is used as a flux.

For coating cast iron articles with solder, after pickling in the acid

solution mentioned, they are heated in a neutral atmosphere and dipped in a bath of molten solder (50/50 grade), upon the surface of which is a layer of ammonium chloride.

Aluminium Bronze Soldering

This alloy is almost as difficult to solder as stainless steel owing to the film of oxide which forms. It can, however, be soldered satisfactorily with the same fluxes as those employed for stainless steel, namely, that given previously or a mixture of boracic acid and potassium fluoride.

Silver Solders

These solders contain copper, silver and zinc and have melting points ranging from about 600° C. to 840° C. They give much stronger joints than the soft solders, but on account of their higher melting points require much higher soldering temperatures; they cannot therefore be employed for heat-treated steels and other alloys which require heat-treatment temperatures approaching those of the solders.

The compositions and melting points of some typical silver solders are given in Table 93.*

TABLE 93
COMPOSITION OF SILVER SOLDERS

Percentage Composition			Melting Point °C.
Copper	Silver	Zinc	
51·0	9·0	40·0	854
34·0	50·0	16·0	774
30·0	45·0	25·0	746
25·0	60·0	15·0	732
25·0	70·0	5·0	776
20·0	65·0	15·0	718
20·0	70·0	10·0	758
20·0	75·0	5·0	776
16·0	80·0	4·0	792

Silver solders with more than 50 per cent silver are essentially silver-copper alloys to which zinc is added to obtain a lower melting point; those with less than 50 per cent of silver are brasses to which the silver has been added to improve the corrosion resistance and mechanical strength properties.

* "Solders and Soldered Joints," *The Automobile Engineer*, July, 1941.

Tin, in silver solder, tends to lower the flow point but increases the brittleness.

Nickel tends to suppress coarse grain growth in the annealed solders. About 15 per cent of nickel is sufficient for this purpose. The tensile strength and hardness of the solder are increased appreciably but the flow point is practically unchanged.

Lead and *iron* are detrimental in silver solders and should therefore be avoided.

A good silver solder should have at least 50 per cent reduction of area before fracture in tension.

The tensile strength of the 75 Ag/22 Cu/3 Zn chill-cast solder is about 18·5 tons per sq. in., and for the 60 Ag/25 Cu/15 Zn one about 28·5 tons per sq. in. Solders with lower silver content have higher tensile strengths than these values.

British Standard Silver Solders

There are three grades of silver solder specified by the British Standards Institution, two being of the silver-copper-zinc class and the other a quaternary alloy with the inclusion of cadmium. The Grade A silver solder has the following percentage composition:—

Cu, 27·5–29·5; Ag, 60–62; Zn, 9–11; total impurities 0·5 (max.).

The Grade B solder composition is as follows: Cu, 36–38; Ag, 42–44; Zn, 18·5–20·5; total impurities, 0·5 (max.).

The melting ranges, from solidus to liquidus, of the Grade A and B silver solders are 690° C.–735° C. and 700° C.–775° C. respectively.

Higher Melting Point Solders

Higher melting point solders include the nickel-copper and copper-silver alloys. The melting points of the former alloys range from 1083° C. for pure copper to 1452° C. for pure nickel, there being no eutectic of lower melting point in the series.

The copper-silver alloys have melting points from the lowest value of about 780° C. for the 28/72 copper-nickel alloy to the highest value of 1083° C. for pure copper. The melting points of this series of alloys are shown in Table 94.

The American Society of Testing Materials (A.S.T.M.) specifies eight different grades of silver solder, including one with 5 per cent of cadmium, having melting points ranging from 1510° F. (820° C.) down to 1250° F. (694° C.). The compositions and melting points of these solders are given in Table 95.

Nos. 1 to 3 are suitable for soldering where a freer flowing solder than the ordinary copper-zinc brazing alloys is required. Nos. 4 and

TABLE 94
Melting Points of Copper-silver Alloys

Copper .	100	90	80	70	60	50	40	30	20	10	0
Silver .	0	10	20	30	40	50	60	70	80	90	100
Melting point °C.	1083	1025	990	940	910	870	820	780	820	890	962

TABLE 95
Composition and Properties of Silver Solders (A.S.T.M.

Grade	1	2	3	4	5	6	7	8
Ag, % .	10	20	20	45	50	65	70	80
Cu, % .	52	45	45	30	34	20	20	16
Zn, % .	38	35	30	25	16	15	10	4
Cd, % .	†	†	· 5	Nil	Nil	Nil	Nil	Nil
Impurities, %* .	0·15	0·15	0·15	0·15	0·15	0·15	0·15	0·15
Melts at, °F. .	1510	1430	1430	1250	1280	1280	1335	1360
Flows at, °F. .	1600	1500	1500	1370	1425	1325	1390	1460
Colour .	Yellow	Yellow	Yellow	Nearly white	Nearly white	White	White	White

5 will flow more freely at lower temperatures than Nos. 1 to 3. They produce strong joints. Nos. 6 to 8 are employed where a high degree of ductility is required.

The compositions and applications of certain commercial silver solders that have been used in this country in the past are shown in Table 96. (See p. 308.)

The fluxes used for ordinary silver solders are of the borax class, e.g. borax or boracic acid, and are applied either as a paste made with water or in a powdered form.

Properties and Applications

In connection with the properties of silver-soldered joints, with suitable solders tensile strengths across the joints of 30 to 40 tons per

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* Maximum.
† The addition of not over 0·50 per cent cadmium to assist fabrication is not considered a harmful impurity.

sq. in. can be obtained; with special solders values up to 50 tons have been recorded. The width of the gap or silver solder layer giving the most satisfactory results is from 0·0015 to 0·002 in.

An advantage associated with the use of silver-soldered joints in electrical work is the high electrical conductivity that can be obtained by the proper selection of the soldering alloy; thus it is possible to employ a silver solder having from 70 to 80 per cent of the conductivity of copper; the higher the proportion of silver the higher is the conductivity in these solders.

TABLE 96

SILVER SOLDER COMPOSITIONS AND APPLICATIONS

Composition per cent			Applications
Silver	Copper	Zinc	
5–10	95–90	––	For thin iron and mild steel sheets.
45	55	–––	A tough alloy for instrument makers; very fluid.
30	50	20	For small brass work.
38·5	46	15·5	For bronze and nickel silver.
9	43	48	For general work on copper alloys.
80	20	–––	Hardest solder.
75	25	––	For general use.
50	50	—	Softest silver solder; will not burn.
15	80	5	Brass, copper and brass-to-copper joints.

Silver solders are employed for soldering iron, steel, copper, silver, gold, and their alloys; for soldering turbine blades into position; for high pressure and temperature small pipe connections; for petrol pipe nipple joints and similar purposes. For automobile and aircraft pipe joints and connections, silver solder is to be recommended owing to its fatigue resistance and reliability; soft soldered petrol and oil-pipe joints invariably fracture with repeated vibration. Brass pipes are sometimes made by bending a sheet of brass into circular form through rollers or dies, and fixing the solder in the form of wire of suitable composition with borax in the overlap. On passing the work through a furnace in which it attains a red heat, the solder runs and makes the joint; the flux is then removed by dissolving, and the tube drawn through dies in the usual way. Joints in beaten metal work, such as the trumpets and horns of musical instruments, are made with hard solder of suitable composition and colour.

Cadmium Solders

A considerable amount of research work carried out during the 1914–18 war period with cadmium as a substitute in part or entirely for the scarcer metal tin resulted in some useful soldering alloys of which those given in Table 97 are typical.

TABLE 97

COMPOSITIONS OF CADMIUM SOLDERS*

Designation	Lead per cent	Cadmium per cent	Tin per cent	Zinc per cent
A	90	10	—	—
B	80	10	10	—
C	90·8	7·8	—	1·4

The melting points were between 400° C. and 450° C., being appreciably higher than for the lead-tin solders, and generally necessitating the use of a blowpipe in place of the usual soldering iron. The solders were found to be satisfactory for joints in sheet metals of copper, brass, lead, steel, galvanized iron and zinc; with the latter metal very sound joints were made. The most satisfactory flux was found to be zinc chloride but resin also gave similar results although the solder did not flow as readily. The B type solder was not as strong as the A and C ones, and eventually the latter type was adopted for general soldering work. This solder does not oxidize easily and at 100° C. it is from 50 to 100 per cent stronger than the 50/50 lead-tin solder and from 30 to 50 per cent stronger than pure tin. It has been used for thinning cable ends, bus-bars and other electrical parts; it was found to be superior to lead-tin solders, but is not satisfactory however for wiped joints as it does not flow freely as a plastic mass.

Cadmium is often employed in silver solders in applications where particularly low melting points and soldering temperatures are required and in this connection it may replace part or all of the copper. In small amounts it does not lower the melting points of the ternary silver solders, except in the case of those alloys low in silver content. When cadmium replaces copper in order to lower the melting point it also reduces the strength and ductility of the solder. When added in order to improve the strength and ductility of silver solders it must be added at the expense of the zinc.

A typical cadmium-silver solder for lower temperature soldering than the ordinary ones is that conforming to the British Standard

* "Cadmium Solders," *Metal Industry*, 26th October, 1923.

Specification No. 206—1941, and having the following percentage composition limits: Ag, 49–51; Cu, 14–16; Zn, 15–17; Cd, 18–20.

This alloy has a melting range of 630° C. (liquidus) to 595° C. (solidus).

Another cadmium-silver solder with a melting point of 743° C. contains 65 Ag; 20 Cu; 5 Zn and 10 Cd (percentages).

A cadmium zinc solder which is employed in place of lead-tin solders in aircraft radiator construction, in connection with the use of ethylene-glycol cooling systems (operating at temperatures well above the boiling point of water), is given in D.T.D. Specification No. 51A. It is employed for tube blocks and casings.

Bismuth Solders

A series of low melting point solders is obtained with lead-tin-bismuth alloys which are suitable for applications which prohibit the use of temperatures employed with the ordinary lead-tin solders, e.g. plumbers' and tinman's solders.

Table 98 gives the compositions and melting points of some typical bismuth solders.

TABLE 98

PROPERTIES OF BISMUTH SOLDERS

Designation	Lead per cent	Tin per cent	Bismuth per cent	Melting Point °C.
A	31·2	18·8	50·0	94
B	40·0	20·0	40·0	113
C	33·3	33·3	33·3	123
D	43·0	28·5	28·5	132
E	47·0	29·5	23·5	151
F	33·2	50·2	16·6	158
G	46·6	40·2	13·2	165
H	50·0	37·5	12·5	178
I	40·0	50·0	10·0	162

These alloys are used with resin or zinc chloride as a flux. The melting point of bismuth is 269° C.

Brazing Alloys

These alloys are used as hard solders for uniting parts in iron, steel, bronze, brass, etc., in order to give stronger joints capable of with-standing much higher temperatures than the soft and ordinary silver solders. The most commonly employed brazing alloy is that known as *Spelter* and consists of copper and zinc; actually it belongs to the

simple brass group of alloys and is used in thin strip or granulated form.

The melting points of the copper-zinc alloys range from 1083° C. at the pure copper end down to 870° C. for the 50/50 copper-zinc alloy.

The limiting proportion of zinc is about 45 per cent, since alloys with smaller proportions are brittle and weak in general.

A commonly used spelter is the 50/50 copper-zinc alloy having a melting point of about 870° C.; it is employed for brazing brasses having melting points above 1000° C. For copper alloys having higher melting points the proportion of zinc is usually decreased below about 45 per cent to give greater strength and temperature resistance, but the melting point of the brazing alloy should always be about 100° C. to 150° C. below that of the alloy to be brazed.

In selecting a copper-zinc alloy for brazing purposes, apart from melting point considerations *it should have a colour* similar to that of the brass or bronze to be united. In this connection as the copper content is increased the colour changes from the golden shade of the 50/50 alloy to pale yellow for the 70/30 copper-zinc alloy; then to a golden colour again for the 75 to 95 per cent copper-content alloy. Above 95 per cent the colour changes to the warm reddish colour of copper.

In instances where the yellow colour of ordinary spelters is objectionable it is usual to employ a brazing alloy of a whiter nature. Such alloys consist of copper and zinc with additions of tin or nickel; the effect of the tin is to render the metal more fusible.

For *brazing iron and steel* an alloy containing 35 to 40 per cent of zinc is used; the same alloy may be employed for copper brazing purposes.

TABLE 99

COMPOSITIONS OF BRAZING ALLOYS

Composition per cent				Applications
Nickel	Zinc	Tin	Nickel	
66	34	—	—	Hardest, suitable for iron and steel.
60	40	—	—	Hard, suitable for iron and copper.
50	50	—	—	Ordinary spelter, for brass and copper.
37·5	50	—	12·5 }	White solders, for nickel silver and iron·
35	57	—	8·0 }	
57·5	25	17·5	—	White solder for brass; more fusible than spelter.
43·4	6·6	50	—	White solder; more fusible than spelter.

More recent brazing alloys are those known as *silico-bronze* and *phosphor copper*. The "bronze-welding" or low temperature welding process using bronze welding rods with the oxy-acetylene flame is really a brazing process. Typical instances are the *Sifbronze* and "*Sil-fos*" processes; the latter employs an alloy of copper, silver and phosphorus melting at about 700° C. The percentage composition of this alloy is as follows: Copper, 80; silver, 15; phosphorus, 5.

Two well-known grades of brazing solders are given in the British Standard Specification No. 263. Grade A has a nominal composition of 54/46 copper-zinc and Grade B is 50/50. Maximum limits are specified for other included elements such as tin, antimony, arsenic, iron, bismuth and lead.

Parts in iron, steel, brass, copper, bronze, etc., joined by the brazing process are fluxed with powdered borax or borax and water paste. *Cast iron brazing* is frequently done with cuprous oxide as a flux.

Another spelter that is *more fusible* than the ordinary copper-zinc ones has the following percentage composition: Cu, 44; Zn, 50; Sn, 4; Pb, 2. In general, however, alloys containing much lead should not be used since the lead does not transfuse with the copper and zinc alloy and tends to reduce the tensile and shear strength of the joint.

Brazing Applications

Brazing is used for a large number of purposes in commercial work and also for repairs in cycle and automobile work. Bicycle and similar tubular frames are often made up of separate components brazed together, the parts being pinned with special pegs in order to hold them together and in the correct positions. Brazing operations are usually conducted in a gas forge or brazing hearth provided with suitable temperature regulation means and it is an advantage if a reducing atmosphere can be employed.

The borax flux employed leaves a very hard slag, or scale, upon brazed joints, which can only be removed by filing, pickling, or sandblasting.

There are, at present, several methods of brazing in which the parts are dipped into a bath of molten spelter, the metal being prevented from adhering to the surfaces other than those to be brazed by coating them with blacking or similar compositions; these methods are economical and lend themselves to quantity production work. The joints made in this manner are more uniform, and there is no possibility of internal stresses owing to the general nature of the heating, as distinct from the ordinary local heating of the blow-pipe or forge.

Another successful method is an electrical one; it consists in connecting the two parts to be joined with the terminals of a dynamo. When the current is switched on, the parts, on account of their high resistance, become heated to a brazing temperature, and the brazing wire, or spelter, which has been previously placed over the joint is melted, and fills the vacant spaces in the joint. With this system a reducing atmosphere of hydrogen, nitrogen, or coal gas may be employed, and fluxes dispensed with.

Pieces of high-speed tool steels are often hard-brazed into iron or mild steel shanks suitably milled out to receive them, using strips of copper between the joints to be brazed and a special flux. The whole tool is then raised to the welding temperature of the copper, and the joint is made. The tool steel can then be hardened and tempered in the ordinary manner, since the temperatures employed are much below the melting point of copper. This method is also applicable to certain other steel and iron joints.

Brazing Cast Iron

In the ordinary way it is very difficult to braze cast iron on account of the carbon present and of the oxides formed during the process; special fluxes are now available for cast-iron work, and with special care fairly good joints can be made.

A process invented by Pich for performing this operation in an ordinary smith's hearth consists in decarburizing the surfaces of the cast-iron parts to be united during the brazing and bringing the molten brass solder into close contact with the cast-iron surfaces at the same time. A copper oxide mixed with borax and in the form of a paste is used for decarburizing the surfaces; this paste is applied to the surfaces of the cast iron after they have been thoroughly cleaned. The parts to be brazed are held in position with iron wire and heated, when the borax is first melted and protects the surfaces from oxidation; it also prevents the copper oxide from being attacked by the oxygen of the air. As the heating proceeds the oxide of copper fuses and liberates its oxygen, which combines with the carbon of the cast iron, with the formation of carbon monoxide and dioxide, and the liberation of copper, which in its turn combines with the brazing brass; the new brazing compound, which now possesses a higher melting point, combines with the decarburized iron. Very strong joints giving almost the same tensile strength as that of the cast iron itself are obtainable with this method.

The "bronze-welding" method is now widely used for cast-iron joints.

Low Melting Point Alloys

Alloys having low melting points, namely, from about 250° C. down to about 45° C., i.e. well below the boiling point of water, have several important applications in engineering and industry.

Some of these are used for the purpose of filling steel, brass, copper and aluminium tubing so that it can be bent cold without flattening or wrinkling. Other alloys are employed for filling fusible plugs which are inserted in the furnace crowns of steam boilers. Should the water level fall so as to expose the metal of the crown the fusible alloy melts into the furnace and thus allows the steam to escape into the latter and to extinguish the coal fire.

Other alloys which have a low melting point—usually from 110° C. to 160° C.—expand slightly on solidification and give sharp mould impressions. They are used for making metal patterns as substitutes for the usual wooden ones employed for moulding purposes in the foundry, for plaster mould impressions, ornamental castings, proof castings of forging dies and moulds, fusible cores for casting moulds, models, dies and formers for sheet metal pressings, etc.

Certain low melting point alloys are used for holding and setting

TABLE 100
LOW MELTING POINT ALLOYS

Description	Lead %	Tin %	Bismuth %	Cadmium %	Melting Point °C.	Remarks
Wood's metal . . .	25	12·5	50·0	12·5	70	For crystal and gem setting.
Lipowitz's alloy . . .	26·1	13·3	50·0	10·6	60	Silver-white. Malleable. For casting delicate objects.
Expanding alloy . .	66·7	—	8·3	25·0	65	Expands on solidification.
D'Arcet's metal . . .	25·0	25·0	50·0	— Mercury	94	
D'Arcet's mercurial metal .	11·0	11·0	22·0	56·0	45	For accurate casts of anatomical specimens.
Newton's metal . . .	31·25	18·75	50·0	—	94	Previously used for boiler plate safety fuses.
Rose's metal . . .	28·0	22·0	50·0	—	100	Previously used for boiler plate safety fuses.
Onion's metal . . .	30·0	20·0	50·0	—	92	Fusible alloy.
Fusible alloy . . .	28·6	14·3	50·0	7·1	70	For boiler fuse plugs, etc.
Fusible alloy . . .	27·6	10·3	27·6	34·5	75	For boiler fuse plugs, etc.
Fusible alloy . . .	35·2	20·0	35·3	9·5	80	For boiler fuse plugs, etc.
Bismuth solder . . .	46·0	27·0	27·0	—	94	Low melting point solder.
Bismuth solder . . .	40·0	40·0	20·0	—	144	Medium melting point solder.
Bismuth solder . . .	44·5	44·5	11·0	— Antimony	160	High melting point solder
Expanding alloy . .	75·0	—	8·3	16·7	145	For accurate casts.
Expanding alloy . .	37·0	63·0	—	—	182	
Expanding alloy . .	77·0	—	—	23·0	249	

punches and dies in their base-plates for press work operations and for rapid and accurate location of blanking, piercing and trimming punches in relation to dies without the need of machining non-working surfaces to close dimensions.

Alloys such as Wood's Metal, having a melting point of about 70° C., are used for holding gems for cutting operations, wireless set crystals, etc. Most of the low melting point alloys contain lead, antimony, bismuth, tin or cadmium. The compositions and melting points of some typical low melting point alloys for various purposes are given in Table 100.

Alloys for Tempering and Heat-treatment Baths

The alloys of tin, lead and bismuth in different proportions have melting points ranging from 94° C. to 162° C. It is thus possible to obtain an alloy with any desired melting point for a special purpose, such as for heat-treatment at the lower temperatures of certain non-ferrous alloys and steels.

TABLE 101

TIN-LEAD-BISMUTH ALLOYS

Percentage Composition			Melting Point °C.	Percentage Composition			Melting Point °C.
Tin	Lead	Bismuth		Tin	Lead	Bismuth	
18·8	31·2	50·0	94	50·2	33·2	16·6	158
17·7	35·3	47·0	98	48·0	36·0	16·0	155
15·8	42·1	42·1	108	45·9	38·8	15·3	154
20·0	40·0	40·0	113	45·0	40·2	14·8	153
27·0	36·5	36·5	117	43·0	43·0	14·0	154
33·3	33·3	33·3	123	41·5	44·8	13·7	160
30·8	38·4	30·8	130	40·2	46·6	13·3	165
28·5	43·0	28·5	132	38·2	49·0	12·8	172
25·0	50·0	25·0	149	37·5	50·0	12·5	178
29·5	47·0	23·5	151	41·5	46·8	11·7	167
33·4	44·4	22·2	143	43·0	45·6	11·4	165
37·0	42·0	21·0	143	44·4	44·4	11·2	160
40·0	40·0	20·0	145	46·0	43·2	10·8	159
43·0	38·0	19·0	148	47·5	42·0	10·5	160
45·7	36·2	18·1	151	48·8	41·0	10·2	161
48·1	34·6	17·3	155	50·0	40·0	10·0	162

The alloys of *lead and antimony* give melting points ranging from that of pure antimony (630° C.), pure lead (327° C.), down to the temperature of the eutectic consisting of 87·5 per cent lead and 12·5 per cent antimony having a melting point of 247° C.

The eutectic of *bismuth and tin* consists of 56·7 per cent bismuth and 43·3 per cent of tin; it has the lowest melting point of the alloys of these metals, namely, 137° C.

The eutectic of *zinc and lead* consists of 97·7 per cent lead and 2·3 per cent of zinc and has the lowest melting point, namely, 318° C.

The eutectic of *tin and cadmium* consists of 48 per cent tin and 52 per cent of cadmium and has the lowest melting point, namely, 177° C.

The eutectic of *lead and cadmium* consists of 82·6 per cent lead and 17·4 per cent of cadmium and has the lowest melting point, namely, 247·3° C. It is possible to obtain alloys of these metals having any desired melting points between those of the metals themselves and of their eutectics.

SOME OTHER USEFUL ALLOYS

Bismuth-Cadmium Alloys

The effect of adding cadmium to bismuth is to lower the melting point of the alloy; further, it tends to reduce the brittleness of the metal. The bismuth-cadmium alloys with lead and tin have low melting points, namely, below the boiling point of water. Examples of these alloys with melting points as low as 60° C. are given in Table 100.

Glass-to-Metal Cementing Alloy

A bismuth alloy used for cementing glass to metal and which is also employed for fastening the metal parts on glass lamps consists of 50 per cent lead, 33·5 per cent tin and 16·5 per cent bismuth.

Alloy for Porous Castings

An alloy for filling blow-holes and defective places in castings before enamelling or painting these consists of 8·3 per cent bismuth, 25·0 per cent antimony and 66·7 per cent lead.

Maximum Expansion Alloy

An alloy which is claimed to have a greater expansion effect on solidification than any other metal or alloy consists of equal parts, by weight, of antimony and bismuth.

Silvering Liquid Alloy

A liquid alloy used for silvering mirrors and the interiors of vacuum flasks contains 80 per cent mercury and 20 per cent bismuth. Another

alloy used for the same purposes has equal parts of mercury, lead, tin and bismuth.

Some Commercial Low Melting Point Alloys

*Cerrobend.** This is a commercial low melting point alloy having a melting point of 71° C. It is used as a filler to fill tubes and moulding for bending operations and is particularly suitable for bending thin copper and aluminium tubing. It can be removed from the bent tubing by heating in steam or boiling water.

Cerrobase is a lead-bismuth alloy with a melting point of 124° C. which does not expand or contract on solidifying. It is used for duplicating wood patterns for foundry purposes, and for taking accurate impressions of moulds, forgings, dies, etc. It is also employed as a nitriding seal for heat-treatment baths, as a fusible metal for safety purposes and for lightning arrestors.

Fig. 144. Method of Holding Punch in Cerromatrix

Cerromatrix is an alloy of bismuth, lead, tin and antimony with a melting point of 110° C., which expands on cooling. It is used for the mounting of dies and punches on base-plates in connection with punching, blanking and pressing operations. The use of this alloy effects both time and cost saving in building up dies and punches and affords accurate and secure location of the punches in relation to the dies. The built-up components can be used for long series of runs on metals up to $\frac{5}{32}$ in. thick. The holes in the base-plate members are usually of dove-tail section and the portions of the punches to be secured by the alloy in these holes are drilled, grooved or serrated so as to afford a strong hold when the molten alloy is poured around them in the hole in the base-plate; a typical method of holding the punch to the base-plate is shown in Fig. 144.

An example of a three-stage progressive blanking and piercing die for making the sheet fibre shape shown in the upper part of the illustration is given in Fig. 145. The punches on the left are located and held by Cerromatrix alloy.

Type Metals.

These are alloys of tin, lead and antimony which are used for type-casting purposes and for making stereotype, i.e. the fixed plates upon the surfaces of which are cast reproductions of the faces of all the type used for complete pages or sets of pages.

* Mining and Chemical Products Ltd., London, W.C.2.

Type metals give sharp and very smooth impressions of the mould and are sufficiently hard—owing to the antimony content—to withstand long periods of printing usage.

Ordinary type metals contain from 5 to 10 per cent of tin, 15 to 30 per cent of antimony and 60 to 80 per cent of lead. The exact composition depends upon the character of the work required. For normal purposes from 5 to 10 per cent of tin, 15 to 19 per cent of antimony
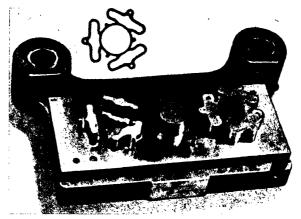
FIG. 145. THREE-STAGE PROGRESSIVE BLANKING AND PIERCING DIE, USING CERROMATRIX TO LOCATE AND HOLD THE PUNCHES

and the balance of lead gives a good hard-wearing and sharp impression taking type metal. These alloys commence to deposit solid constituents at about 250° C. and are usually poured into the moulds at about 265° C.

The addition of a small amount of copper is sometimes made in order to increase the hardness, but the metal is then more difficult to melt and cast as the tin-copper compound commences to deposit from the solution at about 270° C. and an antimonial-copper constituent at a somewhat higher temperature. The compositions of some typical type metals* are given in Table 102.

Copper-zinc Expanding Alloys

It has been observed by Turner and Murray† that slowly cooled alloys containing 85 per cent of zinc and 15 per cent of copper exhibit

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* "Antimony Ores," Imperial Institute Monograph (John Murray, Ltd., London).

† *Journ. Inst. of Metals,* 1909, 2, 98.

TABLE 102

STANDARD TYPE METALS

	Antimony	Tin	Lead
	per cent	per cent	per cent
Standard electrotype . .	4	3	93
Standard linotype . .	12	5	83
Standard monotype . .	18	8	74
Standard stereotype . .	13	4·50	82·50
Ordinary linotype . .	13	5	82
Cheap linotype . . .	11	3·50	85

marked expansions on cooling, the amount of this expansion depending upon the percentage of copper and rate of cooling. During solidification the force of expansion is considerable. Later investigations* indicate that for a copper content of 14·16 per cent the maximum expansion occurs, its value being 0·1064. The hardness and elastic limit of the expanded alloys are low and the alloys contain cracks and voids. In quickly cooled (chill-cast) bars the density varies along the length and also across the diameter of the bar. The copper content is higher and the density lower in the centre of the bar.

The expansion effect fades away at about 5 per cent and 30 per cent copper content respectively.

Britannia Metal

These alloys of tin, antimony and copper, with or without the additions of small proportions of other metals, are employed chiefly for making inexpensive domestic tableware, e.g. teapots, spoons, jugs, and also ornamental objects and toys.

The principal constituents are tin and antimony, with smaller amounts of copper, zinc, lead, bismuth and other metals.

The Britannia metals have a silvery-white colour with a slight tinge of blue. Some typical compositions are given in Table 103.†

G.E.C. Heavy Alloy

An interesting alloy made from tungsten, copper and nickel by the sintering process is characterized by its very high specific gravity and good tensile strength. The alloy in question contains 90 per cent of

* *Journ. Inst. of Metals*, March, 1924.
† "Antimony Ores," Imperial Institute Monograph (John Murray Ltd., London).

TABLE 103

BRITANNIA METALS AND ALLIED ALLOYS

	Anti-mony	Tin	Lead	Copper	Zinc	Bis-muth
	per cent	per cent	per cent	per cent	per cent	per cent
Ashberry metal* . .	15·0	79	—	3·0	2·0	1·0†
Britannia metal (English) .	5·0	94	—	1·0	—	- -
Britannia metal, sheet .	7·80	90·6	—	1·6	—	——
Britannia metal, cast .	9·2	90·6	—	0·2	- -	——
English plate-pewter . .	10	80	1·0	9·0	- -	...
German plate-pewter .	24	72	- -	4·0	.	——
Minofor metal* . .	18·2	68·5	—	3·3	10·0	- -
Pewter	7·0	89·4	1·8	1·8	.	- ....
Prince's metal (for covers) .	15·25	84·75	- -	——	- -	——
Queen's metal . . .	7·1	88·5	- -	3·50	0·9	——
Queen's metal (teapots) .	8·88	73·36	8·88	—	...	8·88
Wagner's metal (fine) .	9·66	85·64	- -	0·81	3·06	0·83

tungsten, 4 per cent copper and 6 per cent nickel. It has a specific gravity of 16·3 to 17, being therefore about twice as heavy as steel.

The tensile strength and yield point are 40 and 37 tons per sq. in., respectively, the elongation on 1 in. being 4 per cent. The elastic modulus is 36×10^6 lb. per sq. in. and Brinell hardness 250 to 290.

The coefficient of linear expansion is $5·6 \times 10^{-6}$ per degree C.

The thermal conductivity is 0·25 C.G.S. units.

The specific resistance is 11·6 microhms per cm. cube.

It is made by adding a mixture of copper and nickel powders to tungsten powder, compressing these by means of steel dies to the required shape and heating to about 1450° C. in hydrogen. The structure then consists of large spherical grains of tungsten embedded in a tough matrix of copper-nickel-tungsten solid solution. The alloy is almost completely resistant to corrosion by the atmosphere and salt water. It can be brazed or silver soldered to other metals and plated with nickel, cadmium or chromium. Components of the alloy can be welded together by a special method in a hydrogen atmosphere.

Developed primarily for radium therapy purposes it has an important engineering application *for engine and machinery balance weights* where its small volume for a given weight has proved an advantage. Another application is for arcing contacts of large oil

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* Employed for making forks, spoons, coffee-pots, teapots, etc. Harder than Britannia metal, but less beautiful.

† Nickel.

circuit breakers. In a test made on two heavy alloy contacts measuring $1\frac{1}{4}$ in. by $\frac{3}{8}$ in., connected in series, it was shown that a current of 130,000 amps. at 6·3 kV per phase could be successfully ruptured.

Konel Alloy

Konel is the name given to a cobalt-nickel alloy, produced by the American G.E.C., which possesses high strength properties at elevated temperatures. The alloy, in addition to its major cobalt and nickel content, contains also iron and titanium. It is made in the electric furnace and has a specific gravity of 8·59.

The tensile strengths at 24°, 400°, 500° and 600° C. are 46·2, 46·3, 36·8 and 29·5 tons per sq. in. respectively. The corresponding elongations are 37·0, 34·0, 33·0 and 18·5 per cent respectively.

The coefficient of linear expansion from 0° to 100° C. is $10·75 \times 10^{-6}$ and from 0° to 700° C., $14·30 \times 10^{-6}$.

The specific resistance values at 0°, 400°, 800° and 1000° C. are 35, 69, 100 and 108 microhms per cm. cube.

The results given are for specimens annealed at 900° C. for two hours. The alloy can be fabricated by the usual methods employed for heat-resistant nickel alloys. It work-hardens rapidly and so requires frequent annealing at 900° to 1000° C., at which temperatures it shows no noticeable tendency to scale and is still quite resistant to the hammer.

Konel is used for the valves and valve stems of petrol and Diesel engines, for steam turbine blades and other applications requiring operation at a red heat. It was originally developed as a substitute for platinum in radio valves; the Konel filaments of these operate at 175° C. lower temperature than those of platinum. The filaments are produced from 20 lb. ingots forged, cold-rolled and drawn through diamond dies to one-thousandth inch diameter. They are then rolled into ribbon 0·002 in. wide and 0·00055 in. thick. Konel has excellent corrosion resistance properties to most acids and its cost in comparison with platinum and iridium—which it has been used in place of—is extremely low.

Batterium Alloy*

This alloy is a high-strength corrosion-resisting one possessing good electrical conductivity and ductility. Its percentage composition is as follows: Cu, 89; Al, 9; Ni and other metals, 2. It contains no tin, lead, zinc or antimony.

The colour is silvery gold.

* Batterium Ltd.

The specific gravity is 7·67; melting point, 1035° C.; tensile strength, 34–45 tons per sq. in., with 35 to 48 per cent elongation; Brinell hardness, 158–168; thermal coefficient of expansion, 0·0000162 per deg. C.

The resistivity is 13·21 microhms per cm. cube at 20° C. The relative conductivity is about 15 per cent of that of copper.

The alloy retains a high percentage of its tensile strength at elevated temperatures. Thus at 400° C. the tensile strength is about 24 tons per sq. in. with 28 per cent elongation (on 1¼ in.); the Brinell hardness is 158 to 167 at this temperature.

Batterium resists corrosion and erosion of alkalis and acids and for this reason is used in the construction of chemical plant. It is readily welded and can be machined with ordinary tools. It is available in sheets, seamless tubes, extruded rod, castings, forgings and stampings. Typical uses are for plug cocks and wheel valves for chemical plant.

Electrical Contact Metals

The metals used for electrical contacts include platinum and its alloys, palladium, rhodium, iridium, gold, ruthenium, tungsten, nickel, copper and silver alloys. The particular metal or alloy used depends upon the service conditions and involves considerations of the current across the contacts, pressure between the contacts, mechanical and electrical wear, tarnishing resistance, impact effects, design of the contacts, etc.

In general the platinum group of metals is best suited to contacts carrying light currents, whereas for heavy currents the silver and silver alloys are preferable.

In instances where the contacts operate under very light pressures the platinum alloys are best since they do not form insulating films of tarnishing products on the contact surfaces. The platinum alloys are also recommended for conditions of heavy wear under severe corrosion and arcing circumstances.

In connection with the arcing limits of contact metals the following values* are of interest—

Platinum	0·8 ampere
Palladium	0·6 -0·7 ,,
Silver	0·4–0·5 ,,
Alloy of 6 per cent platinum, 70 per cent gold and 24 per cent silver	0·2–0·4 ,,
Alloy of 10/1 gold-platinum	0·6–0·7 ,,

* "Contacts Suitable for Instruments," H. Williams, *Journ. Scient. Insts.*, September, 1934.

An inductive energy of 0·25 joule should not be exceeded between the contacts. For severe impact conditions such as those experienced with high-speed petrol engine ignition contact breakers, *tungsten*—which has the high melting point of about 3000° C. and great hardness, viz. about 290 Vickers pyramid hardness number—is often employed. The current values in these applications are low, since, for high amperages and low voltages, tungsten tends to form high resistance oxides; it has also a relatively high electrical resistance.

In order to obviate the latter disadvantages *combinations of tungsten with silver or copper* have been employed, thus obtaining the advantages of the high melting point and hardness of tungsten together with that of the low electrical resistance of silver or copper.

Alloys of tungsten and molybdenum are also employed for contacts owing to their high resistance to wear; moreover, the molybdenum has only a small effect upon the conductivity of the tungsten. Tungsten-nickel is another good wear-resistance contact alloy but it has a higher contact resistance than the platinum series.

Table 104* gives the hardnesses, melting points and specific resistance values of the precious metals used for contacts. In regard to the specific resistances shown it should be noted that the lower these values are the better the metal is as an electrical conductor. The thermal conductivity, upon which the heat dissipation of the contact metal depends, is approximately in inverse proportion to the specific resistance; thus, good electrical conducting metals are also good heat conductors.

Platinum. This metal has a melting point of 1755° C. and a hardness value of 47 (Vickers pyramid diamond value). It is extremely ductile and malleable, but is too soft for most contact purposes although still used for certain relay contacts. It is usual to alloy platinum with other metals such as iridium, rhodium, tungsten, ruthenium, osmium, gold, silver, nickel and copper for electrical contacts.

The effect of alloying platinum with iridium is to harden it, to increase the melting point and the specific resistance, as the percentage of iridium is increased; some values of these quantities are given in Table 104.

When more than 12 per cent of iridium is present the alloy in the annealed state has an increased tensile strength. When *copper is alloyed with platinum* the electrical resistance is increased to a marked extent, a resistance per mil. ft. of approximately 54 ohms being obtained; moreover the alloy is much harder than platinum, namely, about twice the Vickers pyramid diamond value.

* *Electrical Contacts in Precious Metals* (Johnson, Matthey Ltd., London).

TABLE 104

PROPERTIES OF ELECTRICAL CONTACT METALS

	Hardness (Annealed) Vickers Pyramid Numeral	Approx. Melting Point °C.	Specific Resistance at 18° C. Microhms per cm. cube
Pure Metals—			
Platinum	47	1755	10·5
Iridium	421	2290	5·3
Palladium	63	1549	10·7
Gold	23	1063	2·4
Silver	23	961	1·6
Alloys—			
Commercial platinum . . .	55	1755	11·4
10 per cent iridio-platinum . .	110	1810	23·6
20 per cent iridio-platinum . .	200	1855	30·3
25 per cent iridio-platinum . .	250	1870	31·8
30 per cent iridio-platinum . .	290	1885	33·1
H.S.F. platinum alloy (containing tungsten and iridium) . . .	130	1800	22·2
Platinum-iridium-ruthenium alloy ("IRRU")	300	1890	39·0
	Approx.	Over	
Platinum-iridium-osmium alloy:			
No. 540	500	2000	—
Platinum-gold-silver alloy . .	70	1120	16·8
Palladium-copper alloy No. 60 .	130	1240	35·0
33 per cent platinum-silver . .	100	1200	32·4
Palladium-silver alloy:			
No. 501	71	1030	3·8
No. 502	100	1070	5·8
No. 503	165	1160	10·0
5 per cent gold-silver . . .	27	970	2·6
10 per cent gold-silver . . .	28	980	3·6
30 per cent gold-silver . . .	37	1027	7·3
70 per cent gold-silver . . .	72	1060	10·4
Copper-silver alloy No. 510 . .	75	890	2·0
Copper-silver alloy No. 520 . .	108	820	2·1
Standard silver (92·5 per cent) .	50	894	1·9

Nickel and cobalt are also used as alloying elements, the 10 per cent nickel alloy having a lower resistance than the corresponding cobalt one.

Ruthenium and osmium have an even greater hardening effect on platinum than iridium.

These hardened platinum alloys are used for magneto contacts, vibrator adjusting contacts and similar items requiring rapid making and breaking of electrical circuits under relatively heavy impact

,conditions, where corrosion resistance is required to be of a high order. The 15 to 20 per cent iridium alloy has been widely employed for these purposes. The precious metal contact is welded to a base metal shank or screw end as illustrated by the examples given in Fig. 146.*

In connection with the *platinum-rhodium* alloys of varying rhodium content it has been shown that the microstructure of each alloy appears
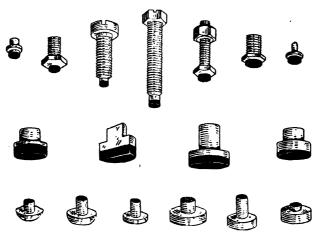
FIG. 146. TYPES OF ELECTRICAL CONTACTS

The contact metal is shown in black

to be that of a solid solution and the temperature coefficient of resistance is a minimum for alloys having 20 to 40 per cent of rhodium; the resistivity is at its maximum between 10 and 40 per cent.

The results of a comprehensive series of tests on platinum and some palladium alloys made by E. M. Wise and J. T. Eash† are given in Table 105. The tests were carried out on these alloys in the form of wire of 0·071 in. diameter in the annealed condition, and cold-drawn to a diameter of 0·050 in., corresponding to a reduction in area of 50 per cent. At the latter diameter the wires were tested in the drawn condition and also after annealing, usually for 5 minutes at different temperatures in an electric furnace.

The results given indicate that *nickel* exerts a very pronounced hardening effect on platinum; the strengthening effects of palladium, iridium, rhodium and ruthenium are also shown.

Platinum-gold-silver alloy (see Table 104) is used in telephone

* *American Machinist.*
† Tech. Pubn. No. 584, *Amer. Inst. Mining and Metall. Engrs.*, 1935.

manufacture for the small contacts used for telephone relays, voice frequency relays and similar apparatus. It is a hard alloy and less expensive to use than platinum, but its arcing resistance is rather lower. It possesses very good corrosion resistance and is considered the next best metal for contact purposes to platinum.

TABLE 105

PROPERTIES OF PLATINUM METALS AND ALLOYS, COLD-DRAWN
(50 PER CENT REDUCTION) AND AFTER RECOMMENDED ANNEALS

Material	Recommended 5 min. Anneal, °C.	Limit of Proportionality, lb. per sq. in.	Ultimate Tensile Strength, lb. per sq. in.	Elongation, per cent on 2 in.	Reduction of Area, per cent
Com. pure Pt	900-1000	27,000 10,000-5,300	36,000 24,000-22,000	2·5 24-34	95 92
No. 1 Pt	1050-1100	27,000 8,500-6,500	36,700 25,000-23,000	3·5 21-29	96 94-95
Pt 95, Ir 5	1100-1200	53,000 23,000-18,000	69,100 41,500-39,000	2·0 23-32	92 95-94
Pt 90, Ir 10	1100-1200	54,000 36,000-30,000	82,200 55,000-53,000	2·5 25-27	94 95-94
Pt 80, Ir 20	1200-1400	100,900 62,000-59,000	140,500 102,000-93,000	2·5 21-20	84·5 89-88
Pt 90, Rh 10	1100-1200	55,600 22,000-17,000	84,300 49,000-47,000	3·0 25-37	90 93-94
Pt 75, Pd 20, Rh 5	1000-1100	51,900 23,500-17,000	85,000 57,000-53,000	1·75 23-29	87 91-94
Pt 95, Ni 5	1000	70,000 33,000	103,100 65,000	2·0 23·5	84 93
No. 1 com. Pd.	800-900	31,800 5,000	46,900 30,000	1·5 30-41	91·5 92-89
Pd 95, Rh 3, Ru 2	1000-1100	46,050 16,000-15,500	61,000 46,000-41,000	2·0 30-36	88·5 92-88
Pd 95, Ru 4, Rh 1	1000-1100	46,300 28,000-21,000	71,500 59,000-55,000	3·0 23-26	84·5 84

Note. Upper values are for the 0·05 in. drawn wire and lower values for the annealed wire.

Palladium-copper alloy (see Table 104) has been specially developed for use in light-duty contacts employed in telephone relays.

The *silver alloys* containing small percentages of platinum, palladium or gold are cheaper than the platinum ones and possess high electrical conductivity. They are harder and have greater corrosion resistance than pure silver.

Standard silver is an alloy of silver with 7·5 per cent copper. It is cheaper than pure silver and is used for the contacts of wireless set switches and thermostatic devices, where the main considerations are rapid dissipation of heat from the contact surfaces combined with good wear resistance.

An alloy of 70 per cent silver, 25 per cent palladium and 5 per cent cobalt possesses good properties in regard to corrosion and wear resistance and it is often employed for small electrical contacts.

Sparking Plug Electrodes

The requirements for these electrodes are that they shall be able to withstand the erosion effects due to the high combustion temperatures and sparking voltages; the latter are of the order of 8000 to 16,000 volts. Further, they must be able to resist erosion effects of leaded fuels.

The metals that have been tested* for sparking plug electrodes for aircraft engine use include ferrous alloys, nickel-chromium alloys, Stellite, tungsten, nickel and nickel alloys with more than 95 per cent nickel. The results of actual tests in engines running on leaded fuels indicated that tungsten showed the least erosion and pure nickel was next in order to it. None of the materials showed any signs of chemical attack and the erosion was confined to a small area.
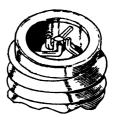
FIG. 147. PLATINUM-IRIDIUM SPARKING PLUG ELECTRODES

Tungsten, however, is not altogether suitable for electrodes since it requires a high sparking voltage; in addition it is too brittle to permit the bending over of the electrodes for gap-adjustment purposes.

High nickel alloys are particularly well suited to sparking plug electrodes on account of their high resistance to erosion and the low sparking voltage needed. They can be used for adjustable electrodes in the form of inserts in a steel central member and in the sparking plug shell; these alloys can readily be worked and bent for adjustment.
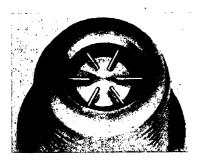
FIG. 148. K.L.G. SPARKING PLUG, WITH SIX PLATINUM-IRIDIUM ELECTRODES

Platinum and platinum-iridium alloy electrodes have been used in some more recent designs of sparking plugs on account of the high erosion resistances, namely, about four to five times that of pure nickel. The alloy favoured is the harder 20 per cent iridium one. Fig. 147 illustrates the Lodge sparking plug electrodes consisting of three square sectioned wires of platinum-iridium, whilst the K.L.G. six-electrode plug is shown in Fig. 148.

Mention should also be made of the nickel-barium alloys, containing

* "Erosion of Sparking Plug Electrode Materials," W. R. Debenham and F. G. Haydon, *Aeron. Research Committee R. and M.*, No. 1744.

from 0·1 to 0·2 per cent barium which are now widely used for sparking plug electrodes. An account of these alloys is given on page 222.

Thermostatic Metals

Although these metals are not alloys a brief account is here included in view of their importance in engineering and industry.

The names *"thermometal"* and *"thermostatic* metal*"* are given to strips of metal made up of two dissimilar metals bonded together by soldering, brazing, welding, rolling or sintering. Assuming that the component metals have different coefficients of thermal expansion, when a flat bimetallic strip of this nature is heated uniformly, owing to the differential expansion effect, the strip will assume a curved shape, the movement being accompanied by the exertion of an appreciable force. This movement, due to temperature increase, may be utilized to perform operations such as opening or closing of electrical circuits when a given temperature is attained; opening or closing valves for regulating the flow of liquids or gases; indicating actual temperatures, for thermometers and pyrometers; operating time switches, and for numerous other purposes.

It is not difficult to estimate the deflection of a bimetallic strip when the dimensions and linear expansion coefficients are known; in this connection a straight narrow strip will form an arc of a circle when heated. Since, however, the bimetal will deflect across its width as well as along its length, a flat section will become curved on heating; by increasing the ratio of thickness to width, however, this effect will be minimized. In most instances this cross-bending effect can be neglected except in the case of bimetallic strips made into the form of helical coils or spirals. The latter, when heated, produce a rotary motion effect; in such coils the cross-bending may either assist or oppose the longitudinal forces tending to deflect the strip.

In regard to the selection of suitable materials the greatest deflection of a given bimetallic strip will occur when the difference between the expansion coefficients is a maximum, so that for this result the expansion coefficient of one metal should be a maximum and that of the other a minimum. The deflection of a flat-section bimetallic strip will vary as the square of the length and inversely as the thickness according to the following relation—

$$d = \frac{k \cdot (T_1 - T_0) \cdot L^2}{t}$$

where d = deflection; T_1 and T_0 the final and initial temperatures;

L the length, and t the thickness of the strip; k is a constant depending upon the metals used.

The values of the linear expansion coefficients* for some of the more common metals are given in Table 203.
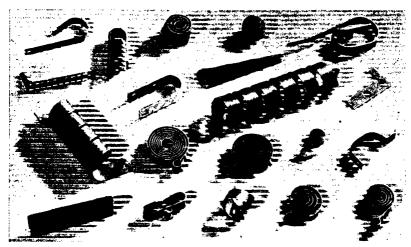
FIG. 149.   EXAMPLES SHOWING SOME DIFFERENT FORMS OF THERMOSTATIC METAL ELEMENTS

TABLE 203

COEFFICIENTS OF LINEAR EXPANSION

Metal	Coefficient
Iron	0·0000119
Nickel	0·0000137
Copper	0·0000166
Silver	0·0000188
Tin	0·0000216
Magnesium	0·0000259
Aluminium	0·0000230
Zinc	0·0000263
Lead	0·0000284

The high nickel steels, with 35 to 40 per cent nickel, have very low expansion coefficients, namely, from 0·0000009 to 0·000006.

There is a wide range of commercial thermostatic metals on the market available in the form of strips made to various shapes, spirals

* *Physical and Chemical Constants*, Kaye and Laby.

TABLE 106

PROPERTIES OF WILCO THERMOMETAL

	Temperature Range of Max. Sensitivity	Constants for Formulae						Electrical Resistance Ohms per sq. mil. ft.	Modulus of Elasticity lb. per sq. in.	Mk.
		STRAIGHT STRIP				COILS				
		K	A	B	C	X	Y			
Standard . .	0–300° F.	0000080	560	70000000	00096	380	400000	68	17500000	S
Highflex . .	0–350	0000072	710	99000000	00086	490	570000	380	25000000	F
Highflex 45 .	0–350	0000080	790	99000000	00096	550	570000	380	25000000	Ⓔ
Scoflex . .	0–350	0000079	770	97000000	00094	520	550000	360	24000000	B
Amplex . .	0–350	0000066	530	80000000	00079	360	460000	180	20000000	A
H.T. Special .	0–350	0000053	500	96000000	00063	350	550000	260	24000000	M
Midflex . .	150–475	0000068	670	99000000	00081	460	570000	360	25000000	Ⓜ
Midflex 46 .	150–475	0000075	740	99000000	00090	510	570000	360	25000000	C
H.T. Constant .	250–600	0000047	450	95000000	00056	310	550000	250	24000000	H
Highheat . .	300–650	0000061	610	99000000	00073	420	570000	330	25000000	Ⓗ
Highheat 47 .	300–650	0000065	650	99000000	00078	450	570000	330	25000000	Ⓧ

The constants given above apply in the following formulae over the temperature range of maximum sensitivity.

STRAIGHT STRIP

$$d = k \frac{(T_2 - T_1)L^2}{t}$$

$$p = A \frac{(T_2 - T_1)wt^2}{L}$$

$$p = B \frac{wt^3 d}{L^3}$$

COILS

$$\Delta = \frac{C(T_2 - T_1)L}{t}$$

$$M = x(T_2 - T_1)wt^2$$

$$M = y \frac{wt^3 \Delta}{L}$$

w = width; $T_2 - T_1$ = temperature change in °F.; d = deflection of free end in inches; p = pull in ounces at free end; Δ = angular rotation in degrees; M = torque in oz. in.; t = thickness in inches; L = length in inches.

and helices, under the name Wilco Thermometal;* it is therefore possible to select the most suitable type of bimetal for any particular application. These thermometals are made for various temperature ranges of maximum sensitivity, namely, from 0° F. to 300° F. up to 300° F. to 650° F.

The properties of the thermometals as known by their trade names are given in Table 106. The values of the constants used in the formulae for deflection, pull and torque are also shown in the table.

It is not possible to enumerate all the applications of thermostatic metals, but the following is a small selection: Automatic control of exhaust heat to carburettor; automatic carburettor choke control; oil gauges; temperature compensation for hydraulic shock absorbers; radiator and cooling system temperature control in automobile and aircraft engines; altitude indicators; circuit breakers; electric clocks; electrical measuring instruments; recording thermometers: radiator shutter controls; fire extinguisher actuating controls; time relays; vulcanizers; gas regulators for constant temperature conditions; electric iron heating controls; oil burners for boilers controls; overload relays; refrigerator heater controls; percolators; electric heaters; transformer indicators: room temperature regulating thermostats; steam traps: sign flashers: signal devices; water heaters—gas and electric. Special thermostatic metals are also available for use in corrosive atmospheres and for high temperature steam purposes.

* H. Wiggin & Co., Ltd.

CHAPTER X

MISCELLANEOUS METALS AND MATERIALS

Antimony

ANTIMONY is a bright bluish-white crystalline metal belonging to the same group of elements as nitrogen, bismuth, arsenic and phosphorus.

It has a specific gravity of 6·7 to 6·86 and melting point of 630° C.; it boils at about 1300° C. and volatilizes at 1500° C.

The specific heat is 0·051.

The coefficient of linear expansion is 0·0000108 per deg. C.

The electrical conductivity is 41·7 microhms per cm. cube.

The principal engineering uses of this metal, some of which have previously been referred to, include its application to alloys such as type metal, stereotype and Britannia metal, all of which give fine sharp castings. It is also useful as a hardening element in lead and is employed in certain bearing metals of the lead-tin class.

Antimonial leads are employed for shrapnel bullets, storage battery plates, sheet lead for acid chambers, cocks and valves in acid plant, for electric cable sheathing and lead pipes.

An interesting use of antimony is for producing the appearance of polished steel on papier mâché.

Antimony and bismuth are used as the elements of a thermo-couple for detecting small changes of temperature.

The salts of antimony have important industrial uses, notably in the vulcanizing of rubber, as paint pigments, glass colouring media, matchbox striking surfaces, mordants, primers of explosive shells, etc.

Beryllium

This is a hard steel-grey metal having a specific gravity of 1·84, being appreciably lighter than aluminium. It has a melting point of about 1285° C.[*] Its specific heat[†] between 0° C. and 100° C. is 0·425.

The metal is extracted from its ore, beryl, by various methods, but is difficult and expensive to obtain in a high degree of purity, the principal impurities being oxygen, iron, carbon, aluminium and nitrogen. By special methods involving the elimination of the oxygen a purity of 99·9 per cent has been obtained.[‡] The Brinell hardness of this

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[*] "Beryllium," *The Metal Industry*, 2nd August, 1929.
[†] Kaye and Laby.
[‡] "Researches on Beryllium," H. A. Sloman, *Journ. Inst. Metals*, 1932.

metal was 60 to 65 and it could be bent backwards and forwards many times before cold-working led to fracture. While the metal was found to be harder than copper or silver it was ductile in the pure form. The brittleness usually ascribed to beryllium is believed to be due to the presence of two allotropes, one hard and the other soft, and to the presence of impurities exceeding 0·1 to 0·5 per cent.

Whilst many claims have been made for beryllium as a possible rival to aluminium and magnesium in connection with strong light alloys it has, to date, proved rather disappointing and has as yet found no industrial applications in this field.

Its principal value, however, is when present in amounts up to about 3 per cent in copper- and nickel-rich alloys. Thus, as shown in Chapter V, the beryllium-copper alloys have found many important applications as spring materials having superior strength properties to phosphor bronze; also for bearings, bushings, and certain types of gears.

Beryllium-bronze chisels will readily cut mild steel and are *non-sparking*, so that they can be used in the vicinity of explosives or inflammables.

Beryllium-copper alloy is also employed for cast moulds used in making plastic material objects; and for resistance welding electrodes.

Beryllium steels, referred to in Volume I, have also important uses on account of their high corrosion resistance and strength properties. Beryllium can be plated on to copper, nickel, iron and aluminium by using a fused bath containing beryllium-oxyfluoride together with an alkali fluoride at a temperature of about 600° C. Copper conductors thus coated possess the high strength determined by the beryllium-bronze coating and the hardness of the latter can be increased by suitable heat-treatment. The coated copper conductors, whilst having the conductivity of the copper core, are stronger than copper, and so are suitable for overhead telephone and power lines.

Beryllium possesses deoxidizing properties which have proved useful in connection with the making of cast copper moulds and other copper castings. It has been found that 0·01 per cent of beryllium gives a dense, smooth and flawless casting of high electrical conductivity.

Beryllium-silver alloys have been found to have good tarnish resistance qualities; from 3 to 5 per cent of beryllium by weight renders silver immune from the tarnishing action of sulphur compounds.

Pistons for petrol engines, possessing good corrosion resistance and much lighter in weight than those of aluminium alloys, have been made of an alloy consisting of 67 per cent beryllium and 33 per cent

aluminium. The tensile strength at 260° C. and the Brinell hardness value after heat-treatment are about the same as for the forged 14 per cent silicon-aluminium alloy. On the other hand the thermal conductivity of the beryllium alloy is only about one-half that of the latter alloy so that suitable design alterations are necessary to ensure that the pistons do not operate at appreciably higher temperatures.

Bismuth

This is a lustrous greyish-white brittle metal with a slight red tinge, belonging to the same chemical group as antimony. It has an atomic weight of 208, specific gravity of 9·9 and a low melting temperature, namely, 269° C.

It is a hard metal but owing to its brittleness can readily be powdered; it is neither ductile nor malleable.

The specific gravity of the molten metal is 10·055 and, as previously stated, that of the solid metal is 9·9, so that it expands on solidification by about 2·3 per cent of its volume. The molten metal can be poured at 6° C. below its solidifying point and still remain liquid, but the temperature rises when it solidifies.

The specific heat is 0·0305 between 20° C. and 100° C.

The coefficient of linear expansion is 0·0000139.

Its electrical conductivity is 1·3* and heat conductivity 1·8 (silver = 100); these are about the lowest values of the metals.

Bismuth is the most diamagnetic metal known, i.e. in its power of being repelled by a magnet.

On exposure to air bismuth oxidizes slightly. When heated to redness it burns with a bluish flame forming a bismuth oxide known as "flowers of bismuth" (Bi_2O_3).

Bismuth has many uses for medical, surgical, electrical and engineering alloy purposes.

It is employed for making fusible alloys, heat-treatment molten alloy baths, electrical fuses, stereotype metal, bismuth-bronzes, bismuth-cadmium low melting point alloys (below 100° C.), solders and castings.

Cadmium

Cadmium is a bluish-white metal obtainable commercially from 99·5 to 99·9 per cent purity and having a brilliant crystalline fracture; it emits a rustling sound resembling the "cry" of tin when bent.

It has an atomic weight of 112·41 and a specific gravity (cast) of 8·604; in the hammered condition the specific gravity is 8·69.

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* 120 to 150 microhms per cm. cube.

The specific heat from 0° C. to 100° C. is 0·0548.

The specific resistance is 6·2 to 7·0 microhms per cm. cube.

The melting and boiling points are 321° C. and 785° C. respectively.

The latent heat of fusion is 13·00 cal.

The tensile strength of the hammered metal is about 6 tons per sq. in. with 44 per cent elongation on 3 in. gauge length.

Its malleability is such that it can be beaten out into thin foil; it can also be drawn out into very fine wire.

The hardness of cadmium in the annealed state is 21·3 to 25·5 Brinell. The coefficient of linear expansion is 0·0000306 per deg. C. [0° C. to 100° C.].

Cadmium is soluble in dilute acids with the formation of the corresponding salts; dilute nitric acid is the best solvent. From such solutions zinc will precipitate the metal in tree-like or dendritic form.

Cadmium, as previously mentioned, forms a number of very useful alloys. These include *copper-cadmium* containing about 1 per cent cadmium which is used for the trolley wire on electric tramway systems; *cadmium solders* used instead of tin solders when tin is scarce; *cadmium-gold* alloys of greenish colour used in jewellery; *cadmium-silver* alloys of excellent malleability used for certain domestic articles made by spinning and drawing; also for *stain-resisting silvers*; *bearing alloys* of low coefficient of friction; *fusible alloys*, such as bismuth-lead-cadmium, bismuth-tin-cadmium and lead-tin-cadmium, for *fusible plugs* in fire-resisting plant and safety devices and electric fuse wires; clichés used to a considerable extent in newspaper printing where metal copies are taken from impressions stamped in papier mâché by a hard type set; also fusible alloys employed in wireless telephony and for crystal detector settings.

Cadmium* is also used in the manufacture of tungsten lamp filaments. An alloy consisting of 42 parts cadmium, 53 parts mercury and 30 parts of tungsten is ground and heated in a mortar; afterwards it is extruded into wire. and finally heated to drive off the alloy and finished by heating in a vacuum to solidify the tungsten.

Mercury cadmium alloys are used in standard electric cells. It is also employed in the oxide form with powdered zirconium silicate in making high temperature-resistor material for use in electric furnaces. It has a low negative temperature coefficient of resistance, even at 1000° C. Cadmium vapour arc lamps give a strong monochromatic

* A fuller account of the applications of cadmium is given in "A General Survey of Cadmium," by C. F. Moore, *Journ. J'·n. Inst. of Engrs.*, 1928.

red light.   Cadmium is also used in association with tin, lead and antimony to make alloys for electric cable covering.

Cadmium salts, such as the sulphide, are used for making paints. The sulphide gives a range of colours from lemon yellow to deep orange red.

A coating of the paint is given to street cars and vehicles over a coat of chromium yellow or a cheaper body, and the cadmium sulphide, being entirely unaffected by hydrogen sulphide, keeps its yellow colour with great permanency. The sulphide is also used for tinting rubber goods, toilet soaps, and candles, and finds employment in pyrotechny on account of the rich blue flame produced during combustion.

Cadmium in various forms is used for colouring glass, porcelain, etc., and in the preparation of enamels. It has been employed to produce some beautiful coloured enamels consisting of cadmium sulphide and selenide combined together; these have been to some extent used for the decoration of articles of jewellery.

During the 1914–18 war, small arms ammunition was provided with a cadmium band on the hard jacketed cartridge ball, which then took the rifling with little wear on the barrel, and thus prolonged the life of the gun; for this purpose large quantities of cadmium were imported by Germany before the war.   Also there was considerable employment of smoke bombs for signalling during the 1914–18 war, in which cadmium was an important smoke-producing component. Sporting shot and rifle bullets are coated by electro-deposition.

Cadmium Plating.   Cadmium is used as a protective coating for steel and brass parts.   Although not so hard as chromium it is easier to apply and if more expensive by weight the cost of the plating per unit area is no more than that of nickel plate owing to the thinner coating required.

Although it will not give such a high polish as nickel, cadmium will provide satisfactory polished coatings for most purposes; it maintains its colour satisfactorily.   After exposure to the atmosphere it becomes dull in time, due to the formation of an oxide film, but the latter affords a protection against further attack.

Cadmium plating will withstand the usual salt-spray test from 50 to 100 hours; it is, however, attacked by most acids, but is superior in its resistance qualities to zinc; moreover, it is very resistant to alkalis that readily attack zinc.

Owing to its high electro-chemical equivalent, which is twice that of nickel, copper, or zinc, cadmium is deposited more rapidly than these metals under similar plating current conditions.

A cadmium film of 0·0002 in. thickness is considered satisfactory

for protective purposes, whereas in the case of nickel a coating of 0·001 in. is necessary.

Cadmium can also be used as an undercoating for deposits of other metals, and nickel can be deposited more easily on cadmium than on zinc: the use of "nickel-over-cadmium" coatings is recommended where a nickel finish with rust protection is desired.

Articles to be cadmium plated must be thoroughly cleaned, one satisfactory method being to immerse them in hot caustic potash solution, wash in cold running water, dip in dilute hydrochloric acid, ar d finally again wash in cold running water. From the pickle dip— which produces a uniform bright surface—the parts go into a cold solution of cyanide of potassium or cyanide of soda in water, the latter being less expensive than the potash. The cyanide dip removes any remaining film left from the air or acid. The acid pickle is not required for brass parts, as the alkaline dip gives a satisfactory clean a d bright surface. No undercoat of copper or other metal is needed for plating cadmium on iron and steel. Plating baths may be either acid or alkaline, the latter b ing largely used. The alkaline bath consists of a water solution of potassium cyanide with the addition of caustic soda.

A most satisfactory electrolyte to give a fine-grained deposit, according to some authorities, is a double cyanide of sodium and cadmium, in which the cadmium ion content is low. One satisfactory plating solution consists of: water, 1 gal.; sodium cyanide, 9 oz.; cadmium oxide, 1 oz.; potassium hydroxide, 1 oz., and $\frac{1}{4}$ oz. "brightener" (black molasses). For mechanical plating the sodium cyanide should be increased to 12 oz. and the cadmium oxide to 3 oz.; the "brightener" should be reduced to $\frac{1}{8}$ oz.

A current density of 6 to 20 amperes per sq. ft. and a voltage of 5 to 6 across the bus-bars appears to give the best results. If the parts are moving, or the solution is agitated, the current density can be increased, with consequent reduction in time required for plating. The solution may also be used either cold or hot. With a hot solution the time of plating can be reduced considerably. Ordinary still-tank plating with a cold solution gives a plate about 0·0002 in. thick in about 15 minutes. After the parts are removed from the plating bath, they are rinsed in cold water and then in hot water to aid the drying.

Cadmium plating is extensively employed for such articles as wireless components, domestic appliances, typewriters, calculating and cash registering machines, various types of instrument parts, for replacing nickel plate on metal toys, for automobile and aircraft parts, screws, nuts, pins and washers, etc.

Cobalt

Cobalt is a brilliant silvery metal of atomic weight 59 and specific gravity 8·6. It melts at 1490° C.

The commercial cobalt contains about 96/98 per cent of the metal.

In regard to its physical and mechanical properties cobalt is, after iron, the most magnetic metal; further, it retains its magnetism up to about 1000° C. At 1115° C. it becomes non-magnetic.

Cobalt forms one of the constituents of an excellent magnet steel known as cobalt steel, particulars of which are given in Volume I of this work.

The following are the principal properties—

Tensile Strength (Cast)		.	.	.	15·0	tons per sq. in.	
,, ,, (Annealed)	.	.	.	16·0	,,	,,	
,, ,, (Rolled)	.	.	.	44·0	,,	,,	
Brinell Hardness	.	.	.	.	124–130	,,	,,
Specific Heat (15°–100° C.)	.	.	.	0·107			
Specific Resistance	.	.	.	9·71 microhms per cm. cube			
Temperature Coefficient of Resistance (0°–160° C.)	.	.	.	.	.	0·0033	

Cobalt is an important element in certain tool steels, as it improves the cutting properties. It forms a constituent of Stellite, a well-known extremely hard metal-cutting material having cutting properties superior to the best high-speed tool steels.

Cobalt is used as an electrical alloy, known as *Cochrome*, in place of the resistance material Nichrome for electric heaters and stoves.

The cobalt K.S. steel, now widely used for magnets, in the tempered condition has a coercive force three times that of the best tungsten steels.

Cobalt is also used for protecting the surface of iron and steel parts exposed to corrosive influences. It is deposited, electrolytically, about 15 times as rapidly as nickel. Cobalt plated parts have a whiter appearance and are harder than nickel.

Chromium

Chromium is a steel-grey metal of extreme hardness obtained from chrome iron ore (chromite); it is much harder than steel, and will scratch glass. If the metal contains carbide impurities it is even harder and approaches diamond in this respect.

Chromium has a specific gravity of 6·92, and melts at 1520° C. Its specific heat at 20° C.–50° C. is 0·104.

Its electrical resistivity is 2·6 microhms per cm. cube.

Chromium has many engineering applications as a constituent

of alloy steels in association with nickel, vanadium, or molybdenum. It also gives stainless and heat-resisting properties to certain steels.

Chromium confers high electrical resistance properties on nickel, well-known examples being Nichrome, Fer-Nichrome, and Kromore; such alloys are used for heating elements of electric stoves and fires.

Chromium also forms an important constituent of chromium magnet steel, a much used substitute for ordinary steel on account of its better magnetic properties.

Chromium Plating. One of the most important applications of chromium, however, is in connection with the plating of other metals; in this respect it is superior to nickel as it does not oxidize in air to any appreciable extent. When electro-deposited, chromium is an attractive metal, slightly bluish in tint, and extremely hard. Although chromium itself is so hard, the deposit is usually so thin that an article after plating is very little or no harder than before. Thus, if the base metal is soft, the finished article is likewise, and may be scratched as readily as the original metal. On the other hand, chromium deposited on hardened steel cannot be touched with a file. Its hardness has led to its extensive use on gauges, which, when electro-plated, for example, to a depth of about 0·002 in. with chromium, yield greater service than any other gauges so far tested. Gauges thus treated have a very enhanced life, and also possess an advantage in that chromium is readily attacked by hydrochloric acid. This will not touch steel, and it can be used to remove the plating after the gauge is worn, when it may be re-sized by a new coating of chromium. It is therefore possible to use the same gauge for an indefinite period. Other directions in which chromium plating methods have been tried out include the coating of the wearing parts of motor-car engines, such as pump-shaft spindles, gudgeon-pins, crankshaft journals, cylinder barrels (Listard process), etc. Obviously, the application of chromium plating has two purposes; one as a permanent decorative effect, and the other to prolong the life of wearing mechanical parts.

The electro-deposition of chromium is conducted on the same lines as nickel plating, and similar electro-depositing processes, although there are certain considerations in connection with the work that demand slightly different equipment.

Chromium plating has been successfully applied to replace nickel plating on the motor-car parts that are subject to weathering. While nickel-plate tarnishes readily and wears off rapidly under successive polishing, chromium retains its brilliancy and needs only an occasional wiping with a cloth to remove dust, or the usual application of the hose, sponge, or chamois leather to restore the original lustre. Due to

its hard surface there is no danger of wearing or rubbing off the plate. The best results are undoubtedly obtained on non-ferrous metals, and to-day such articles as water-taps, lavatory and bath fittings, electric, gas, ship and hotel fittings, motor-car interior body fittings, are being successfully chromium-plated. As a finish for domestic utensils and fittings it has a strong appeal to the housewife, since nothing but a rubbing with soap and water is required to keep the articles bright and clean.

Chromium coatings when thin are usually not impervious. As a deposit on iron or steel, chromium does not have a detrimental effect on riveting, as the chromium is passive and exerts no such electrolytic action as do cadmium and zinc. Such articles as surgical instruments and other objects intended for indoor use and always in a dry condition may be conveniently coated with chromium, but iron or steel products or components subject to conditions likely to promote rusting should be preceded by copper and nickel plating. In such applications the chromium is especially useful for its tarnish resistance, though it does add appreciably to the protection against corrosion by the copper and nickel.

Chromium plating is more expensive than nickel plating. Actually, it is usually estimated that the cost is from three to four times that of nickel plating, but the longer life of the chromium-plated product or component, the elimination of constant cleaning, extreme brilliancy of the deposit, and its hardness are claimed to more than compensate for the increased cost.

In connection with the use of chromium for plating automobile and aircraft engine gudgeon pins, in order to increase considerably their wear-resistance properties, these parts are hardened, ground and lapped before plating, the plating requiring only a short immersion in the bath. The method employed is automatic, and the coating is about 0·0001 in. thick on each side. Radiator shells, lamp trimmings, and other parts are likewise receiving chromium protection. It is also being used on cutting tools. The chromium plating on knives or dies used to cut paper and leather is said to add greatly to the life between grindings. In the case of shearing knives, the plating is on the side of the knife and the grind is on the edge, so that the chromium is in service indefinitely. The same is true in milling cutters. Chromium-plated gear cutters are said to have three to five times the life of plain cutters. Drills, micrometers, spindles for machine tools and cylinder bores are among other numerous subjects for chromium plating.

In connection with the nature of the coatings obtained, it has been found that chromium when thickly deposited gives a brittle layer;

Main and Crank Journals

Chromium-plated Valves

Petrol Engine Cam Surfaces

Gudgeon Pins

Wearing Surfaces of Gauges Chromium-plated

Plug Gauges

Ring and Plug Gauges

Radiator, Lamps, Mirror, and Wind-screen Fittings

Fig. 130. Some Typical Applications of Chromium Plating to Motor and Engineering Parts

for this reason articles subjected to shock should be given a medium to thin coating.

Generally speaking, the harder chromium deposits are obtained at the higher current densities.

In regard to the electro-plating baths, practically all the baths employed for chromium deposition appear to be derivatives of Sargent's*
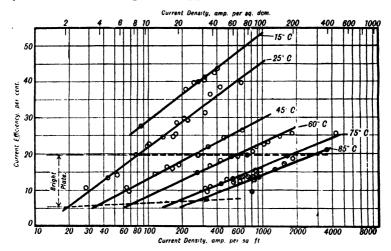
FIG. 151. ILLUSTRATING RELATION BETWEEN CURRENT DENSITY AND EFFICIENCY IN CHROMIUM-PLATING BATHS FOR DIFFERENT TEMPERATURES

solution, and consist essentially of chromic acid (200 grs. to 600 grs. per litre) with relatively small amounts of sulphuric acid or chromium sulphate (from 2·5 gms. to 10 gms. per litre). Sometimes chromic oxide, Cr_2O_3, is added, but the important factor is the sulphate content added to the bath either as free acid or as chromium salt.

One drawback to chromium-plating processes is the high current density required; this is about ten times that of nickel.

Not only is the current density high, but it is very important to have the bath at the correct temperature. Thus, it has been authoritatively shown that at 25° C. a current density of 4 amps. per square decimetre gave a bright chromium deposit at about 12 per cent efficiency, but that at a bath temperature of 70° C. to 80° C. the same efficiency was only obtained with 60 amps. per square decimetre.

Fig. 151 shows the relationship between the current efficiency and

* "Electrolytic Chromium," by G. J. Sargent (*Amer. Electro-chem. Soc.*, 1920, vol. xxxvii, p. 479).

the current density in chromium-plating baths for different temperatures. It will be observed that the conditions for obtaining a bright deposit are shown on the diagram. It is usual to heat the bath *before* commencing to plate, and to maintain the bath at a uniform temperature.

Chromic acid is particularly corrosive, so that glass vessels are used for small baths, but larger ones are often housed in steel tanks or lead-lined wooden vats.

Iridium

This metal belongs to the platinum group. It has an atomic weight of 193 and specific gravity of 22·4. The melting point is about 2290° C. It is a hard whitish metal resembling steel and is quite brittle when cold; it is malleable at a white heat.

Iridium is difficult to fuse and is inoxidizable.

It is employed as an alloy with platinum to give a much harder metal for high impact contacts in electrical apparatus, e.g., ignition contact-breaker contacts; also for fountain-pen points, watch and compass bearings. The iridio-platinum alloy is used in thermo-couples.

Iridium is not soluble in acids. It forms a useful series of alloys with copper, lead, gold and mercury.

Lead

Lead is a very malleable and ductile metal, having a silvery-white crystalline appearance when freshly fractured.

Lead is not appreciably elastic, and it flows under very low stresses.

The specific gravity of pure lead is from 11·3 to 11·4 in the solid state and about 10·37 in the fluid state, so that there is an increase in volume of about 9·9 per cent from the cold solid to the liquid state.

The tensile strength of lead varies from 1500 to 3000 lb. per sq. in.; the compression strength is somewhat indefinite, but lead in a mould will withstand compressions up to 30 tons per sq. in. without breaking down, although the metal flows continuously. The flow pressure for ordinary lead specimens is 0·75 ton per sq. in. The value of E is $0·72 \times 10^5$ lb. per sq. in.

The fatigue limit of pure lead is about $\pm$ 400 lb. per sq. in.

The Brinell hardness, using a 1 cm. ball with 100 kg. load, is from 3·2 to 4·5.

The coefficient of linear expansion of lead is about $28·4 \times 10^{-6}$ per ° C.

The thermal conductivity of pure lead at 16° C. is 0·083, and at 100° C. the value is 0·082.[*]

[*] Kaye and Laby.

The melting point of lead is 327° C., and the boiling point at atmospheric pressure 1525° C.

The specific heat of lead is 0·0305 between 20° C. and 100° C., and at 300° C. its value is 0·0338.

The electrical resistivity at 18° C. is 21 to 28 microhms per cm. cube, and the temperature coefficient of resistance 43×10^{-4}.

Lead is considered to be self-annealing since after deformation it soon recovers its initial softness.

Lead oxidizes in air and is slightly soluble in pure water, but in water containing carbonates or sulphates a coating of these lead salts is formed which protects the metal from further action.

Lead is a constituent of many commercial alloys, such as white-metal, bearing metals, lead bronzes, type metal, soft solders, etc.

Antimony and also tin, as previously shown, have definite hardening effects upon lead.

Tellurium in amounts of 0·05 to 0·10 per cent imparts improved properties to lead, for the latter then becomes amenable to work-hardening and its tensile strength is much higher than that of ordinary lead. Tellurium lead is used for sheeting and pipe purposes since weight can be saved if the alloy is substituted for lead itself.

Ternary alloys of lead having 0·5 per cent antimony and 0·25 per cent cadmium or 1·5 per cent tin and 0·5 per cent cadmium are also much stronger than lead; such alloys are now used for cable sheathing, lead pipe and sheet.

In regard to the former alloy this has a fatigue limit of $\pm$ 1650 lb. per sq. in., i.e. about four times that of pure lead.

Lead coatings are sometimes applied to iron and steel articles for protective purposes, and provided that the lead is perfectly alloyed or bonded, they are very effective. The electrolytic method of depositing lead does not always yield reliable results, the coating being porous, so that the lead-dipping process is preferred.

Terne sheets, which are frequently employed in place of tinned iron sheets, are made by dipping cleaned and pickled steel or iron sheets into molten lead.

Many articles are now coated by first dipping with tin-lead alloys and then wiping; the interiors of domestic iron and cast-iron utensils, steel pipe, and other fittings are frequently coated with these alloys.

The "white lead" so largely used in compounding paints and putty is a mixture of lead carbonate and hydrated lead oxide. It is a poisonous substance, an amount of more than 2 milligrams per day being considered a dangerous dose.

Manganese

Manganese is usually employed in the alloyed form, in commercial work, with iron, as ferro-manganese or spiegeleisen. The specific gravity of manganese is 7·4, and its specific heat at 14° C. to 97° C. is 0·122.

It melts at 1260° C. and boils at 1900° C.

Manganese, when alloyed with iron, oxidizes rapidly in the air and it is therefore much used as a deoxidizer of molten iron.

Manganese is present in all steels, whether carbon or alloy, in varying small amounts, and it forms a useful constituent.

Manganese steel contains from about 7 to 20 per cent of manganese, possesses marked strength and toughness and is non-magnetic.

When used in copper-zinc or copper-tin alloys it adds to the strength and toughness, as in the case of manganese bronze.

Molybdenum

This important element in alloy tool and other steels is a hard silvery-white metal having a specific gravity of 10·0 and a melting point of 2450° C.

The specific heat is 0·072 C.G.S. units at 15° C. to 91° C.

The electrical resistivity is 5·7 microhms per cm. cube.

Molybdenum can be formed into wire by hot-drawing from ingots made by pressing and heating the powdered metal at a temperature below the melting point. These ingots must be worked hot since they are brittle when cold. After hot-working has proceeded to a certain stage the metal becomes ductile when cold.

The worked metal can be annealed at about 1050° C. so as to produce a fine grained structure.

The swaged and hot-drawn wire (1000–1300° C.) has a tensile strength for wires of 0·025 to 0·125 in. of about 66 tons per sq. in. with 4 to 5 per cent elongation. In the annealed condition this value falls to about 55 tons per sq. in. with 3 per cent elongation for the fine grained metal, and to about 19 tons per sq. in. with 30 per cent elongation for the large grained material produced by higher annealing temperatures. Molybdenum is used for X-ray targets, but its principal application is as an alloying element in steel.

Niobium

This silvery-white metal belongs to the same group of elements as tantalum, the physical properties of which are somewhat similar. It has an atomic number of 41, atomic weight of 92·9 and specific

gravity of 12·75. Its melting point is 1950° C. and boiling point 3300° C. The Brinell hardness of the pure metal is about 75. It has somewhat remarkable gas absorption properties which are superior to those of tantalum, and is used in the construction of the metal parts of radio valves.

Niobium is readily soluble in molten metals at normal melting temperatures. It has special applications as a constituent in small amounts in austenitic stainless steels for preventing "weld decay." In 6 per cent chromium steel its presence increases oxidation resistance at high temperatures and shortens the period of annealing necessary for the improvement of ductility. These properties are unaffected by welding and oxy-acetylene cutting.

The addition of niobium (and also tantalum) to nitriding steels has been found to increase greatly the rate of thickening of the nitrided skin, so that the period of time for nitriding can be shortened considerably; in this connection a content of 1 per cent niobium is sufficient for the purpose. Further reference to this subject is made in Volume 1 of this work.

Palladium

This is a rare metal of the platinum group, white in colour and possessing a certain degree of ductility and malleability. It has an atomic weight of 106 and specific gravity of 11·4.

It is capable, in the spongy condition, of absorbing a considerable volume of hydrogen; thus a palladium wire used as the negative electrode of an electric cell will absorb 936 times its own volume of hydrogen. Palladium has a melting point of 1549° C.

The specific resistance at 18° C. is 10·7 microhms per cm. cube.

Palladium forms a useful series of alloys with silver for electrical contact purposes; such contacts are harder and less liable to corrode than pure silver ones. These alloys are dealt with in Chapter IX.

Platinum

Platinum is a bright greyish-white heavy metal with a specific gravity of 21·5 and melting point of 1752° C. to 1756° C.

It is both malleable and ductile, is heavier than gold and does not oxidize or tarnish in the air.

Owing to its relative softness it is usually hardened by alloying with iridium for commercial electrical applications.

The specific heat is 0·0324 C.G.S. units at 18° C. to 100° C.

The coefficient of linear expansion is 0·00000954. This value is

practically identical with that of the glasses used in chemical apparatus so that platinum wires for conveying electric currents can effectively be sealed into the glass without risk of air or gas leakage.

The thermal conductivity is 0·166 C.G.S. units at 18° C. and 0·173 at 100° C.

The specific resistivity is 11 microhms per cm. cube at 18° and 14 at 100° C. The temperature coefficient of resistivity is 0·0038 from 0° C. to 100° C.

Platinum is unaffected by ordinary mineral, animal and vegetable acids, but is attacked by *aqua regia*. It will withstand exposure at a high temperature to attack by a large number of chemicals, but is affected at a red heat by alkalis, nitrates, cyanides, phosphorus, arsenic, etc.

On account of its general immunity to chemical action by most materials it is employed for crucibles, dishes, foil, spatulas, wire, weights, etc., for chemical laboratory and industrial purposes.

It forms a useful series of alloys with gold, copper, silver, nickel and certain other metals. In this connection an alloy resembling gold, known as "mock gold," consists of 7 parts of platinum and 16 parts of copper (by weight). Platinum alloyed with iridium is used for electrical contacts.

Platinum bronze consists of 1 part platinum, 90 parts nickel and 9 parts tin.

Platinum dental alloy consists of 5 parts platinum, 3 parts gold and 4 parts palladium.

Rhodium

This is one of the precious metals of the platinum group. It has an atomic weight of 103 and specific gravity of 12·44. It is of white lustrous appearance and has a high melting point, namely, about 1907° C. Although used to some extent as a hardening medium in certain alloys and in the construction of electrical pyrometers, its principal application is for providing an untarnishable plated coating on various articles. This coating is extremely hard; its hardness lies between that of chromium and nickel.

Rhodium owes its "stainless" qualities to the fact that it is a very inert element, entirely unaffected by acid action; thus, whereas platinum is attacked by *aqua regia*, rhodium is quite unaffected; similarly it is immune to the action of vegetable and animal acids.

Among the commercial applications of rhodium mention may be made of its *use for plating* jewellery, silverware, pen nibs, the radiators of expensive cars, precision-measuring weights, parts of

microscopes, hydrometers, lens mountings, nautical instruments, gauges, microphone parts, musical instruments, camera fittings, surgical apparatus, safety razors, propelling pencils and metal reflectors.

In regard to its *use for coating reflectors*, for searchlights, cineprojectors, floodlights, etc., it not only gives a high polish, but its reflectivity approaches closely that of silver; moreover, it is almost as white as the latter metal. The plating process is not a difficult one, but certain precautions must be taken to ensure sound results.

Silicon

Silicon has a specific gravity of 2·3, and is a hard element which melts at about 1200° C.* and boils at about 3500° C., although there is some doubt as to the exact temperatures.

Silicon is the common constituent of silica (SiO_2), quartz, and glass, all of which are noted for their hardnesses.

Fused silica is used for electrical insulating at high temperatures.

It has a resistivity of the order of 0·06 ohm-centimetre, and this value decreases rapidly at higher temperatures.

Silica has a dielectric constant of 3·5 to 3·6, and a dielectric strength of 600 volts per mil.

The coefficient of linear expansion from 0° C. to 100° C. is $0·50 \times 10^{-6}$, and from 0° C. to 1000° C. $0·54 \times 10^{-6}$.

The specific heat of crystalline silicon at 57° C. is 0·183.

Quartz is a form of silica, or oxide of silicon (SiO_2), and is extremely hard; it occurs in colourless transparent crystals of hexagonal and prismatic form. Quartz is often used as a high temperature optical substance, for the observation windows of combustion chambers, for sparking plug bodies, and similar purposes.

Fused silica ware is much used in chemical work, and for the leads of high temperature electrical thermometers, the exposed bulbs of thermometers, etc.

Quartz fibres can be drawn to very fine sizes, and these are employed for the suspensions of optical and electrical instruments. The tensile strength of these fibres is about 10×10^9 dynes per sq. cm.

Silicon has an appreciable beneficial effect upon the strength of iron and steel.

Silicon is employed in metallurgical processes in the form of ferrosilicon, silico-spiegel, ferro-silicon-aluminium, silicon-aluminium, etc.

Silicon bronzes and silicon-aluminium-copper alloys are noted for their high tensile strength, hardness, and non-corrodible properties.

* **Kaye and Laby.**

Silver

Silver has a specific gravity of 10·5 and melting point of 961° C.

It has the best heat and electrical conductivities of the metals and is very ductile and malleable.

The thermal conductivity at 18° C. is 1·006 C.G.S. units.

The coefficient of linear expansion is 0·0000188 at 20° C.

The specific heat is 0·556 at 0° C. and 0·059 at 427° C.

The specific resistance of 99·9 per cent silver is 1·63 to 1·66 microhms per cm. cube at 18° C. and 2·13 at 100° C.

The temperature coefficient of increase in resistance from 0° C. to 100° C. is 0·0040.

Silver has numerous industrial applications, some of which have been referred to previously in this volume. Thus, it is employed for electrical contacts which have to carry heavy currents; it is, however, usual to alloy the silver with other metals such as copper, platinum or palladium in order to increase the hardness and corrosion resistance for contact purposes.

In the United States an extensive research on the possible industrial applications of silver and its alloys has been undertaken by the Bureau of Standards in conjunction with American silver producers. Already, it has been tested out with satisfactory results for such purposes as the main constituent in aircraft engine bearing metal (used in steel-backed bearings); for electrical machine slip-rings and silver-graphite brushes for rotating electrical contacts; for lead-silver solders with 2 to 6 per cent silver as an alternative to lead-tin solders; as a catalyst in the oxidation of ethyl alcohol; in the form of silver salts for fungicides; for lining cans used for food products and for lead-silver battery grids.

In instances where aluminium sheet or foil has been used for its high corrosion resistance or high reflectivity silver plating on various metals can be substituted. Silver is also being used as an *undercoating* in place of nickel for chrome-plating purposes.

Experiments have also been made* to determine the strength of *extruded tubing* from an alloy of 3·5 per cent silver and 96·5 per cent tin. A bursting stress of 2500 lb. per sq. in., or almost double that of pure tin, was obtained; this is apparently far in excess of any working pressure encountered in distilled-water lines where this material is finding commercial use. Tests on threaded joints showed that the alloy had a tensile strength 25 per cent greater than joints made with pure tin tubing. For certain installations it would seem

* *Automotive Industries*, 15th August, 1941.

feasible to use threaded connections in distilled-water lines if the tubing were made of the silver-tin alloy.

Its use for electro-plated goods, silverware, jewellery and, alloyed with 7 to 8 per cent of copper, for coinage purposes is well known.

Tantalum

Tantalum is a silvery-white heavy metal, which in recent years has become of increasing importance in many fields of application. In the pure state it can be hammered, drawn, rolled and generally cold-worked; if heated to redness and hammered repeatedly it becomes so hard that a diamond will not scratch its surface. This hardening effect occurs also when it is combined with carbon; for this reason a small percentage added to certain steels greatly increases their hardnesses. As mentioned in Volume I, tantalum content steels and carbide alloys are now employed for several important purposes.

Tantalum has an atomic number of 73 and atomic weight, according to different authorities, of 180·9 to 181·5; the differences are probably due to the difficulty experienced in obtaining the pure metal.

The specific gravity is 16·6 so that the metal is a heavy one.

The melting point is about 2850° C., so that it is appreciably higher than that of platinum (1755° C.) and iridium (2290° C.). The boiling point is 5300° C.

The electrical resistivity at 18° C. is 14·6 microhms per cm. cube and the temperature coefficient between 0° C. and 100° C. is 0·0033.

The coefficient of linear expansion is 0·0000079 per ° C., which is rather less than that of platinum, namely, 0·00000954.

The specific heat is 0·0365 C.G.S. units.

The tensile strength is given* as 60 tons per sq. in. and Brinell hardness 75 to 125 for the pure unworked metal.

Tantalum is unaffected by the majority of corrosives, with the exception of hydrofluoric acid. None of the mineral acids, including *aqua regia*, has any effect upon it : it is similarly immune to chemical action by phosphoric and other organic acids such as tannic, oxalic, carbolic and formic. It withstands almost indefinitely the corrosive action of sea-water, sulphurous gases and industrial atmospheres.

The high strength of the metal permits its use in thin sheets and tubes for chemical purposes even when high pressures are employed: its good heat conductivity gives it an advantage over glass and

* "Tantalum and Niobium," R. Genders, *Sands, Clays and Minerals,* April, 1938.

ceramics for many chemical processes. Tubes of 0·015 to 0·020 in. thickness will withstand a pressure of 150 lb. per sq. in.

When heated in air above redness it rapidly oxidizes, so that annealing and other heating processes must be done in an inert atmosphere or *in vacuo.*

Tantalum can be welded satisfactorily if suitable precautions are taken to prevent oxidation. The metal is now weldable by electric spot, seam, butt and roller processes in inert atmospheres or under a liquid surface; it cannot, however, be welded by oxy-gas methods.

Tantalum when used in an *electrolytic cell* in contact with a dissimilar metal such as lead allows electric current to flow in one direction only; for this reason such a combination is used for small alternating current rectifiers such as those employed for radio apparatus.

Tantalum is also used for *electrolytic condensers* in which the tantalum elements are made by a powder metallurgy process. These elements if punctured by high voltage *become self-healing,* the film re-forming over the hole.

Tantalum, on account of its physical properties and resistance to "dusting," is particularly useful as a material for lamp and radio valve filaments, anodes and grids; it is, however, more expensive than some of the other alternative metals and alloys.

Tantalum absorbs gases when it is heated; it is able in this way to absorb 740 times its own volume of hydrogen, giving a coarse-structured brittle material.

The tantalum carbides are claimed to be superior in their metal-cutting properties to tungsten carbides when used to "tip" steel tools.

Tin

Tin is a white lustrous metal, which is soft and fusible; it possesses little strength, and is principally employed in the alloyed form with other metals, to which it gives marked beneficial properties.

Tin is commercially supplied in two grades, namely, Grade *A,* assaying not less than 99·75 per cent of pure metal, and Grade *B,* assaying not less than 99 per cent of pure metal.

The tensile strength of cast tin varies from 2500 to 5000 lb. per sq. in., the average value being about 3500 lb. per sq. in., with practically no elongation.

Tin melts at 232° C. and boils at 2270° C. under atmospheric pressure.

It has a coefficient of linear expansion of $21·65 \times 10^{-6}$.

The thermal conductivity of tin at 18° C. is 0·155.

The specific heat of tin is 0·0552 between 19° C. and 99° C.

The electrical resistivity at 18° C. is 11·3 microhms per cm. cube, and the temperature coefficient of resistance is 45 × 10⁻⁴ between 0° and 100° C.

Compared with silver (100), the electrical and heat conductivities are 12·4 and 14·5 respectively.

The chief impurities in commercial tin are lead, iron, copper and arsenic and occasionally sulphur, silver, bismuth and antimony.

Tin forms an important constituent of commercial non-ferrous alloys such as the bronzes, gunmetals, Delta metals, bearing metals, whitemetals, solders, pewters, certain nickel silvers, etc.

Tin is practically non-corrodible under ordinary atmospheric conditions, and it is widely used for coating copper and iron, domestic vessels, iron and steel sheets, etc.

Tungsten

This is a hard grey metal having a high specific gravity, namely, 18·7 to 19·1 according to the condition, and a melting point of about 3000° C.; this is the highest melting point of all the elements with the exception of carbon (about 3600° C.).

Tungsten ingots used for working are made from the powder which is heated to a temperature approaching the melting point and subjected to pressure. The metal thus formed is malleable and ductile when hot, but brittle when cold.

The coefficient of linear expansion is 0·0000044 at 27° C. and 0·0000073 at 2027° C.

The thermal conductivity at 18° C. is 0·35 C.G.S. units.

The specific heat is 0·033 C.G.S. units at 20° C. to 100° C.

The specific resistance at 25° C. is 5·0 microhms per cm. cube.

Tungsten possesses a high tensile strength, the actual value of which depends upon the condition of the metal. In this connection the following values given by Z. Jeffries* show the extremely high strengths of fine tungsten wires (see Table 107, p. 352).

The drawn tungsten wire can be treated at a higher temperature than any other metal without losing the effects of work-hardening.

Tungsten wire produced by swaging and drawing processes is ductile, i.e. it can be drawn again in the cold condition, but it is not malleable for if hammered it splits into fibres. Unlike other metals which are annealed—or their ductility restored—by heating to certain temperatures, tungsten when thus treated becomes brittle when it cools down ; it can only be rendered ductile again by hot-working

* *Kent's Mechanical Engineers' Year Book*, 11th Edit. (Wiley).

(below the recrystallization temperature). Tungsten oxidizes slowly in air at ordinary temperatures until a protective film of oxide forms, when further oxidation is inhibited. It is practically immune to attack by hot nitric, sulphuric and hydrochloric acids, but is dissolved by hydrofluoric acid containing some nitric acid. It is slowly acted upon by hot *aqua regia* and by hydrogen peroxide.

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TABLE 107

TENSILE STRENGTH OF TUNGSTEN

</div>

Condition	Dimensions or Diam. in Inches	Tensile Strength Tons per sq. in.	Condition	Diam. in Inches	Tensile Strength Tons per sq. in.
Sintered tungsten ingot .	0·2 × 0·25	8·05	Drawn wire .	0·00550	168·5
Swaged rod .	0·216	22·3	Drawn wire .	0·00396	215·5
Swaged rod .	0·125	47·7	Drawn wire .	0·00114	263·0
Swaged rod .	0·026	96·0	Drawn wire .	0·00100	290·0
Drawn wire .	0·018	118·0	Drawn wire .	0·00050	312·0

Tungsten itself is used principally in the form of wire for the filaments of radio valves and incandescent lamps; for the projecting element of projection lamps, where it is heated to incandescence by a resistance heater unit; for X-ray targets; for the contacts of magneto and coil-ignition contact heaters; for tips of gramophone needles of the semi-permanent type and for electric furnace resistors and lamp filament supports.

Tungsten forms an important element in high-speed tool and magnet steels, the 18 per cent tungsten steel being a typical instance of the former.

Tungsten carbide is a very widely used metal-cutting material employed to tip steel shank tools; it enables much higher machining speeds to be used than for alloy tool steels.

Vanadium

This rare metal is a white lustrous metal which is harder than quartz, non-magnetic and with a specific gravity of 5·8 (crystalline) and 5·5 (powder) and melting point of 1720° C. It oxidizes slowly in air at ordinary temperatures and more rapidly when heated, forming a series of five oxides.

It is not attacked by hydrochloric or hydrobromic acids, cold

sulphuric acid or cold alkalis, but dissolves readily in hot sulphuric acid and caustic potash.

It forms alloys with iron, copper, nickel, cobalt, aluminium, tin, platinum and compounds with silicon, phosphorus, nitrogen and carbon.

Vanadium in small amounts, usually of the order of 0·25 per cent, in steel improves the toughness and impact or shock resistance of the metal.

It is a scavenger and removes both the oxides and nitrides in molten steel baths leaving the metal indirectly toughened.

Vanadium also improves the mechanical properties of steel castings and cast iron; in the latter metal it assists the carbon retention in the combined form.

It is usually employed commercially for steel-making purposes in the form of ferro-vanadium; other forms include cupro-vanadium and aluminium-vanadium.

Zinc

Zinc is a bluish-white metal which is moderately ductile and malleable, but to a much less extent than copper. It is most ductile between 100° C. and 150° C., and can be worked to any desired shape, but outside these limits it becomes brittle. It has a specific gravity of 7·19.

Commercial zinc is supplied in the sheet form, as "spelter" (flat rectangular ingots from 1 to 2 in. thick), or in the granulated form.

The tensile strength of cast zinc varies from 2500 to 3500 lb. per sq. in., with practically no elongation.

Zinc, after being compressed under a stress of 20 tons per sq. in. at 100° C., has a tenacity of about 11 tons per sq. in.

Zinc melts at 419° C., and readily volatilizes and burns in air with bluish-white fumes of zinc oxide. Zinc boils at about 918° C.

The coefficient of linear expansion of zinc is about 26×10^{-6}.

The thermal conductivity of zinc is 0·265 at 18° C.

The specific heat of zinc is 0·092 between 20° C. and 100° C.

The electrical resistivity at 18° C. is 6·1 microhms per cm. cube, and the temperature coefficient of resistance is 37×10^{-4} between 34° C. and 100° C. Compared with silver (100), the electrical and heat conductivities are 29 and 36 respectively.

Zinc is a useful constituent of non-ferrous alloys such as brasses, bearing metals, certain bronzes, high tensile aluminium alloys, German silver, whitemetals, die-casting alloys, etc.

Zinc is practically incorrodible under ordinary atmospheric conditions, and is therefore widely used.as a protective coating for iron and steel, the surfaces being "galvanized" or zinc-deposited by various processes.

Zinc is widely used in connection with *zinc alloy die-castings* and also for *sheet-metal forming dies*.* In some instances one of the two components of the press unit is of zinc alloy and the other of rubber or lead. Such tools are used in the aircraft and other sheet-metal industries for limited quantities of pressings in soft metals, e.g. aluminium and magnesium alloys.

Rolled zinc is used commercially for a variety of purposes, principally in the forms of stampings and pressings. The metal not only offers a high resistance to atmospheric corrosion, but is easily fabricated and can be electro-plated satisfactorily with nickel, chromium, brass and silver. The fabrication of rolled zinc is similar to that of many of the other common metals; the same dies can be employed in most instances. It is necessary, however, to observe certain precautions in drawing operations.

Rolled zinc is best worked at 70° F., or slightly higher; the working qualities fall off rather quickly below this temperature. The upper working temperature limit is about 100° F. It is advantageous to use a lubricant such as soapy water (neutral) for drawing operations.

The rolled metal *is readily soldered* with 50/50 lead-tin solder, but it should not be overheated as excessive grain growth accompanied by loss in strength would occur. *A stronger solder for zinc* contains 55 per cent of lead, 30 per cent tin and 15 per cent cadmium. Acidulated zinc chloride is used as a flux.

Apart from electro-plating, rolled zinc can be buffed to a high polish and treated with plain or coloured lacquers and enamels.

When metals, other than nickel, are to be plated it is advisable to use nickel as a base or primary coating.

Rolled zinc pressings include radiator caps, instrument cases, instrument dials (plain and perforated), domestic casings, decorative panels, automobile pressings for decorative or utility purposes, embossed sheet metal articles, clock cases, etc. In most instances these parts are electro-plated or enamelled.

Zinc alloy wire containing up to 10 per cent aluminium with about 0·4 per cent copper has been used in Germany as a substitute for aluminium and copper for electrical conductors. The rolled wire, of 0·07 in. (1·80 mm.), has a tensile strength (10 per cent Al) of 27 to 30

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* An account of these dies is given in *Sheet Metal Industries*, June and July, 1941.

kg. per sq. mm, (17·2 to 19 tons per sq. in.) with 45 to 30 per cent elongation.

The Galvanizing Process. Iron, steel and other metal parts can be given a coating of zinc by the process of dipping them into a bath of molten zinc. This leaves the articles with a deposit of zinc (or zinc-lead in some instances) which affords a protection against atmospheric corrosion influences. The articles to be coated are first cleaned thoroughly by sand-blasting, or pickling in a 5 to 10 per cent hydrochloric acid bath and then washing in clean water and drying.

Before dipping in the molten zinc the parts are treated with sal-ammoniac for fluxing purposes. After dipping in the molten zinc bath, which is maintained at about 450° C., the articles are withdrawn, allowed to drain or are shaken in order to remove any surplus zinc; alternatively, they may be brushed over with a tow mop or brush.

Objects such as rods, wires, strips or plates may be drawn through the bath, and wiped mechanically with asbestos wipers as they leave the bath. It is often considered advantageous to add a zinc-aluminium alloy consisting of about 20 per cent of aluminium to the molten zinc in order to give better fluidity. The frosted appearance of galvanized articles, such as steel sheets, is obtained by adding *tin* to the zinc.

The deposit obtained commercially varies from two to five-thousandths of an inch, equivalent to from 1½ oz. to a little over 3 oz. of metal per square foot. The actual thickness of deposit obtained depends, however, on the temperature, time and mechanical cleaning factors; and to a lesser extent upon the purity of the zinc bath.

In this respect the electrolytic method has the advantage of giving a uniform coating of pure zinc, as against a non-uniform coating of impure zinc obtained in many cases.

Another advantage of the electrolytic method lies in the fact that it is unnecessary to heat the steel or iron objects, except in rare instances, so that the mechanical properties of the base metal are not adversely affected as they may be if heated to 450° C. In this respect, objects such as steel springs cannot satisfactorily be zinc-coated by the hot dipping process. The nature of the coating obtained by the latter process is quite different from the electrolytic layer, which consists of practically pure zinc.

The metal in the galvanizing bath, owing to its great solvent powers, is seldom purer than about 98 per cent, the impurities consisting usually of lead and iron.

The results of investigations carried out by Bablik indicate that even with pure zinc baths there is not a pure zinc layer on the iron or steel articles. Microphotographs reveal the fact that commencing

with the iron base there is (1) a high iron solid solution layer; (2) a layer consisting of $FeZn_3$ and solid solution; and (3) the outer and thicker coating consisting of zinc with small amounts of iron-zinc alloy.

In the case of electrolytically deposited zinc there is a thin iron-zinc phase layer next the iron, and then the pure zinc layer.

Sherardizing. This zinc coating process consists in first cleaning thoroughly the iron or steel articles by a pickling and neutralizing method as for hot galvanizing, and then placing them in intimate contact with zinc dust (usually with the addition of zinc oxide and powdered charcoal). The articles are heated with the ingredients mentioned in a metal container that can be rotated during the process.

The condensed zinc gradually percolates into the ferrous article, the degree of penetration depending upon the temperature of the drum container and the duration of the process.

The temperature may vary from 300° C. to 450° C., whilst the period of heating ranges from 2 to 4 hours. At the end of the heat-treatment the articles are allowed to cool gradually in the container, and are then separated from the zinc dust.

Sherardized articles have a dull-grey appearance due to the coating of zinc, the thickness of the coating being of the order of a few thousandths of an inch.

The structure of the zinc deposit obtained is different from that with the electrolytic or dipping methods, and with the employment of pure zinc dust the surface layers are of pure zinc. Moreover, there is apparently no definite interruption in the iron content of the various layers, this content increasing uniformly as the base-iron is reached.

In order to prevent caking and to reduce the amount of zinc oxide necessary, a quantity of sand is sometimes added to the zinc dust; this also results in a brighter finish being obtained on the final coating.

Objects up to 15 ft. in length by 1 ft. square section can be Sherardized and complicated surfaces given a uniform coating of zinc. The method has been widely used for steel window casements, springs, aircraft fittings, scaffolding fittings, bolts, nuts, chains and small castings of complex design. It is also employed as the base for many decorative finishes in architectural iron work.

Zinc can also be sprayed on to metal and non-metallic surfaces by the *Schoop process*, employing a pistol for feeding the zinc wire or powder. The latter is melted by an oxy-gas flame and the molten metal is sprayed on to the work by compressed air. In this instance the bond between the sprayed zinc coating and the metal is purely

mechanical, there being no intermediate alloy layer. The coating is continuous and firmly locked to the base surface. The advantage of this method is that it can be applied to all kinds of fabricated steel work so that weld, riveted and other joints can be thoroughly protected. The minimum thickness of coating is 0·002 in., but coatings up to 0·01 in. are frequently employed.

Zirconium

Zirconium is a silvery-white metal which at ordinary temperatures resists to a high degree atmospheric corrosive action. It has a specific gravity of 4·15 and a melting point of about 2300° C.

The electrical resistivity is about 170 microhms per cm. cube at normal air temperatures.

It has a greater affinity for oxygen than silicon at high temperatures and gives a greatly increased recovery of silicon in finished steel for this reason ; it is also effective in removing the final traces of oxygen and nitrogen from the steel.

Zirconium has been used in small percentages, viz. of about 0·35, in association with 3 per cent of nickel in making steel for armour plate on the Continent, and it is now sometimes used in the production of extremely tough and resistant steels. Such steels have been utilized for the making of high-speed tools and for similar purposes. "Cooperite" is an alloy of zirconium and nickel. This is a high-speed steel of high cutting efficiency, and it is claimed that its resistance to corrosive influences is also very high.

Another interesting technical alloy is one of zirconium and aluminium which is stated to be an almost entirely non-corrodible metal and one, also, which is extremely resistant to oxidation at high temperatures.

This zirconium-aluminium alloy possesses the interesting property of "selective radiation." In virtue of this property, electric lamp filaments drawn from the alloy emit a greater amount of light when heated by the electric current than the amount of light theoretically corresponding to the temperature of the filaments. Thus the zirconium-aluminium alloy acts most efficiently as a converter of heat energy into light. Such a property has many future technical and commercial possibilities.

The strong affinity of heated zirconium for nitrogen has been utilized in the production of the solid compound zirconium nitride, which when treated with water gives rise to ammonia—a fact of interest and utility in connection with nitrogen fixation from the atmosphere.

MISCELLANEOUS MATERIALS

Abrasives

Abrasives of various kinds are widely used for engineering and industrial purposes. These are all characterized by the fact that they belong to the hardest materials known and are usually employed in powdered form as grinding pastes with oil; with suitable bonding materials; in grinding wheels; abrasive papers or cloths and abrasive slips and stones. The more widely used abrasives are the natural ones, including diamond, emery, corundum, flint, garnet, quartz, tripoli, sand, pumice, etc. In addition there is a group of artificial abrasives including silicon carbide, aluminium oxide, tungsten carbide, etc.

The natural abrasives used for grinding wheels, stones, abrasive cloths and papers are crushed to powder form, the fine sharp particles being graded according to their screen or size for different applications.

Artificial abrasive wheels contain a more uniform size and grade of abrasive, and are generally preferred to natural abrasive wheels.

The two principal methods of making artificial abrasive wheels are (1) *the vitrified* and (2) *the silicate* ones.

In the former method the dry abrasive mixture is placed in metal moulds and vitrified under intense heat.

The silicate method uses silicate of soda as a binder, the material then being run into moulds and subjected to heat in a suitable oven. More recently *phenolic resins* have been used in many cases instead of the silicate of soda, and the abrasive mixture moulded under heat and pressure as in the plastic moulding process. The abrasive wheels thus made are much stronger than the silicate ones, but are not so strong as the vitrified wheels.

Other binding materials for lighter purposes are *shellac* and *vulcanized rubber*, the latter being much stronger than the former.

In addition to the manufactured abrasive wheels and stones, *natural stones*, consisting of sand grains cemented with a natural binding material, are employed for sharpening edge tools, but they are inferior in their grinding performance to artificial wheels, since they are usually softer, run at much lower speeds and must be used "wet."

The "sand" particles in these stones consist of quartz mixed with lime, mica and felspar; the uniting material often contains lime.

The hardness of minerals is usually expressed on the Moh scale, which shows the relative hardnesses of ten selected minerals so arranged that each of these will scratch those of lower number on the

scale, but will not be scratched by them. The following are the orders of hardness of the selected minerals on the Moh scale—

TABLE 108
MOH'S SCALE OF HARDNESS

Material	Order of Hardness	Material	Order of Hardness
Talc	1	Orthoclase . .	6
Gypsum . . .	2	Quartz . . .	7
Calcite . . .	3	Topaz . . .	8
Fluorspar . . .	4	Corundum . .	9
Apatite . . .	5	Diamond . . .	10

It will be observed that this method gives the relative hardnesses as determined by the scratch method.

The following are some values of hardnesses of typical abrasive materials expressed on the Moh scale—

Diamond	10·0
Tungsten carbide	9·7–9·9
Boron carbide	9·7
Silicon carbide	9·5
Aluminium oxide (corundum) . . .	9·0
Agate	7·0
Flint	7·0
Vitreous pure silica	6·5
Abrasive garnet	6·0–7·5
Felspar	6·0

Aluminium oxide is an artificial corundum made by fusing bauxite in an electric arc furnace. It has the chemical formula Al_2O_3, and forms colourless crystals which are used as an abrasive. The specific gravity is 3·7 and melting point about 2050° C. It is obtainable in various grades and the crystals are very small but extremely hard and sharp. The larger abrasive grain sizes are made up of many crystals. The aluminium oxide abrasives are usually employed for grinding hard, tough and strong metals including steel castings, and for cylindrical grinding on all but the hardest steels.

Typical abrasives of this class include the commercial ones known as Alundum and Aloxite.

Silicon carbide is made in the resistance electric furnace by fusing together sand and coke with sawdust, using salt as a flux. It has the chemical formula SiC and its specific gravity is 3·1 to 3·2. The melting point is about 2200° C. The electric furnace product consists of large crystals which are broken down by crushing to obtain the smaller

ones used for abrasive purposes. The powdered material is used as a powder abrasive, for coating paper and making grinding wheels, hones and abrasive slips and stones. In general silicon carbide abrasives are not so tough as aluminium oxide ones, but are harder and therefore used for grinding the hardest metals, including certain cemented carbide products. Silicon carbide abrasives are known under various commercial names, e.g. Carborundum, Crystolite, Crystolon, Carborite, etc.

Garnet is the name used to distinguish a group of minerals of a crystalline nature possessing both toughness and hardness. These differ appreciably in their hardness, methods of fracture and colour; the clearer and more uniform crystals are employed for jewellery purposes. The abrasive garnets of industry are employed principally for coating cloth and paper, the latter form being preferred to quartz and sand-paper in the woodworking industry. The best abrasive garnets are the deep-red crystals known as *Almandite*, with a hardness of 7·5 (Moh). In instances where a harder abrasive cloth or paper is required the artificial aluminium oxide is used.

Sand. There are several kinds of sand used in industry, including the abrasive ones consisting of crushed quartz and flint, and the hard siliceous kinds employed in making glass and porcelain.

Sand-paper, for woodworking purposes, consists of graded quartz and flint crystals bonded to a tough flexible paper with a strong animal glue.

Tripoli is a fine granular white siliceous material obtained by crushing tripolite. When finely ground it is used as a paint filler; also as a rubber filler. The grade known as "Once Ground" (O.G.) is used for buffing and polishing metals and glass. The "Double Ground" (D.G.) grade is employed for finer polishing and also for foundry parting. For buffing purposes tripoli is usually sold in stick or briquette bonded form.

Emery is a hard natural form of alumina (aluminium oxide) coloured with oxides of iron and manganese. It is crushed into fine crystals of various sizes which are graded for different abrasive purposes, chiefly for grinding powders and emery papers and cloths. It is not, as a rule, so pure or uniform as the artificial aluminium oxide and silicon carbide products.

The numbers usually employed to designate the sizes of grains of emery, corundum and proprietary abrasives range from 10 for the coarsest to 200 for the finer grades, these numbers indicating the number of meshes per linear inch through which the abrasives will just pass. For finer grades than 200 the term "flour" is employed,

and the degree of fineness is indicated by letters such as 0, 00, 000; in another system the letters CF, F, FF, FFF, etc., indicate progressive degrees of fineness.

Asbestos

Asbestos is a mineral fibre composed of hydrous silicate of magnesia with a small amount of iron oxide and alumina. It occurs naturally in chrysotile, tremolite, amosite, crocidolite, etc.

Asbestos of the harsh fibre variety contains less water than the soft fibre kind, and if the latter be heated to a temperature that will drive off some of the water, there results a substance which is so brittle that it crumbles between the fingers.

Asbestos melts at a temperature of from 1200° C. to 1550° C., according to the source from which it is taken. It is an excellent heat insulator, and is widely employed in the form for insulating furnaces, steam and exhaust pipes, boilers, etc. It is often combined with magnesium carbonate, hair, or with wool felt, and used for lagging steam pipes, an outer casing being employed for holding it in position.

Asbestos, when powdered or in the form of fibres, is sometimes kneaded into a dough with water and used for stopping up holes and cracks in small muffles, furnaces, bearing metal, shells, etc.

It is also frequently employed for making moulded shapes to withstand high temperatures; one well-known commercial form of this material (known as "Everite"*) is supplied as corrugated sheets varying in size from 4 to 10 ft. long, by 30 in. wide, of $\frac{1}{4}$ in. thickness, and with corrugations of 3 in. pitch, the weight being 2 lb. per sq. ft. This, together with similar asbestos cement roofing and building materials, is fire-proof, non-conductive, acid and weatherproof.

The specific gravity of asbestos is about 3·1, a cubic foot weighing 193 lb.

The specific electrical resistance is of the order of 16×10^2 ohms-centimetres, and in the composite forms, such as moulded asbestos and asbestos wood, it is much used for electrical insulators.

Asbestos is supplied commercially in the form of twine, rope, wool or flake, thin paper, mill-board, jointings and moulded shapes, etc. It is used with a thin copper shell for internal combustion engine exhaust pipe and silencer gaskets and sparking plug washers.

More recently fire-proof suits of asbestos cloth have been used successfully for men engaged in fighting fierce fires. The Bell heavy suit consists of two layers of asbestos cloth, the outer layer being

* The British Everite Works Ltd.

of hard wearing texture. Between the two layers the suit is padded with flexible asbestos material. The feet of the wearer are encased in boots completely covered with asbestos. The detachable helmet has a double mica window with an air space between; the crown of the helmet is crashproof. The suit, which weighs about 50 lb., can be put on in 40 sec., and a person thus clothed can enter the fiercest fire with safety, remaining in it for about 2 min.

Celluloid or Xylonite

This material is composed essentially of pyrolin (soluble gun-cotton) and camphor (oil). Xylonite is a proprietary grade of celluloid.

It can be produced in a variety of forms and colours, and is much used for fancy goods, imitation tortoise-shell, toys, and cheap, light moulded articles.

Celluloid is very slightly hygroscopic, and can be moulded into any form by softening in boiling water.

Celluloid is also used for covering metal steering wheels, bicycle handles, grips and levers, in order to render them heat-proof and permanently clean.

Celluloid is very inflammable, and quickly ignites; for this reason much attention has been given to the question of rendering it fire-proof by mixing it with other ingredients, such as ferric perchloride in alcohol solution, bromide of camphor, and castor oil, etc.

The specific gravity of xylonite is about 1·35, and the electrical resistivity from 2×10^{10} to 30×10^{10} ohms-centimetres.

The *surface resistivity*, i.e. the resistance per unit length of a strip of unit width, of xylonite varies with the humidity of the atmosphere. For a relative humidity of 50 per cent, the surface resistivity is about three times the volume resistivity value previously given. For 85 per cent humidity its value is $0·2 \times$ volume resistivity.

The *refractive index* of xylonite is about 1·5; this is higher than for water but less than that of glass.

Xylonite is, relatively speaking, quite elastic at normal tempera-tures, but as it is heated the elasticity falls off until at 70° C. to 100° C. the material becomes quite plastic.

In common with certain other organic materials its elastic limit and tensile strength are influenced by the rate of loading. Thus it may undergo plastic deformation with the application of a small force applied for a long period, but for rapid loading it shows a com-paratively high elastic limit. For these reasons the values often given for this class of material show considerable variations.

Typical samples in ordinary tensile testing machines show tensile strengths ranging from 3000 to 8000 lb. per sq. in., and elastic limits of 1500 to 2000 lb. per sq. in.

The coefficient of linear expansion of xylonite is approximately 0·0002 per deg. C.

Xylonite is practically non-hygroscopic and completely resistant to neutral solutions of mineral salts. It is unaffected by weak acids; for this reason it has been used for accumulator cases. The concen-trated acids, however, definitely attack the material.

Celluloid is soluble in amyl-acetate and acetone, and this liquid is often employed for cementing celluloid, accumulator repairs and similar purposes; solutions of celluloid in amyl-acetate are sometimes used for covering bright steel and other metal surfaces for protection purposes. Celluloid has more recently to some extent been replaced by the almost non-inflammable cellulose sheeting.

Cork

Cork is derived from the bark of certain trees, such as the cork oak (*quercus cuber*), and is a light-coloured, porous substance of very low density.

Its specific gravity is about 0·24, and a cubic foot of cork weighs about 15 lb.

There is only one other commercial wood of lighter density, namely, *balsa*, which weighs only 7 lb. per cub. ft.

The structure of cork consists of an aggregation of minute air-vessels, provided with thin, strong watertight walls, so that if the material is compressed it behaves more like a gas than an elastic solid; unlike the behaviour of a spring, which exerts a pressure pro-portionate to the linear amount of compression, cork, when compressed, exerts a pressure which increases in a more rapid manner and varies, approximately, inversely as the volume.

The effect of the permeability of the cork to air, however, causes a gradual, but only partial, loss of compression elasticity under pro-longed loads. The volume of the air-cells in cork constitutes about 50 per cent of the whole bulk; if steeped in hot water, the volume of cork is increased from two to three times. This effect is made use of in connection with the bottling of liquids, the corks being treated in this way before being forced into the necks of the bottles.

The elasticity of cork is, to a certain extent, permanent; thus, the corks of bottles of from 10 to 20 years of age invariably expand when withdrawn.

When compressed, there is a certain amount of permanent set,

due to the escape of part of the air vessel contents, but when the load is released a very slow recovery occurs.

Cork is used for stoppers of all kinds, for heat insulation purposes (refrigerators, oxygen bottles, etc.), sound-proof linings to rooms, floats, washers for the caps of vessels and tanks, vibration insulators, life-belts and life-buoys, etc.

Cork in Engineering Work. Cork has many industrial uses, more particularly in engineering and building constructions. Apart from its use as a sound absorbing medium to obviate the effects of echo and sound conduction in buildings, as an ingredient of tiles and cork lino, it has an important application in connection with the elimination of vibration in machinery. It is now being widely used in slab form to insulate machines, ranging from small fans to large engines and dynamos, against the transmission of noise. Another important application of this material in automobile engineering is in connection with plate clutches. For this purpose cylindrical inserts of cork are arranged in one or more discs forming the rotating members; these bear against steel plates affixed to the other member forming the clutch unit. On account of their high coefficient of friction, sweet running action, and long wearing properties, cork-lined clutches have been found to give extremely long service under exacting conditions. Cork in the form of compressed impregnated particles, i.e. cork dust, is now used for washers or packing pieces, for crankcases and cylinder cover joints, for headlamp covers and petrol joints. On account of its elastic, or "giving," and oil, petrol, and water resisting properties, this material appears to be most suitable for such purposes.

Diamond

Diamond, the purest form of crystallized carbon, is the hardest of known materials, having a hardness of 10 on the Moh scale, and is able to scratch all other materials. It also possesses the lowest compressibility of all materials. The specific gravity is 3·5.

The diamonds used industrially, as distinct from those employed for jewellery, are of the black or coloured variety, known as "boarts," "ballas" and "carbonate." These diamonds when set in suitable steel holders are used for glass-cutting; the turning of abrasive materials which are known to wear down ordinary high-speed tool steels and even the tungsten carbide ones; for wire-drawing dies, rock drills, abrasive discs for grinding tungsten carbide tools, etc. Among the metals and materials upon which the diamond turning tool will give considerably longer service than any other tool are brass,

bronze, copper, whitemetals, aluminium, fibre, Bakelite, porcelain, hard rubber and numerous other moulded plastic materials.

Diamond tools, on account of their relative brittleness, cannot be used satisfactorily for machining steels or cast irons, since when subjected to heavy tool pressure the diamond is apt to crack or splinter. Aluminium alloy pistons are usually turned with diamond tools. As an instance of the durability of such tools it may be mentioned that a tool used on an Ex-Cell-O boring machine, with a diamond weighing about half a carat, bored more than 200,000 pistons before it had to
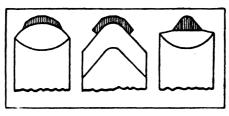
FIG. 152. THREE TYPICAL SHAPES OF DIAMOND TURNING TOOLS

be reset; the total length of chips removed was 9000 miles. In this operation the dimensions were held to an accuracy of 0·00015 in.

Fig. 152 illustrates three typical diamond-tipped tools used for turning aluminium alloy pistons. The first and second tools are very similar, although the former has seven cutting facets and the latter three. The tool on the extreme right is similar in shape to a round-nosed steel turning tool.

These tools are used on pistons which are rough-turned by ordinary steel tools to within about 0·005 in. ot finished dimensions. They are then finished with the diamond tool at a cutting speed of 200 ft. per min. and a feed of 120 per in. An extremely smooth finish is obtained in this way.

The diamond is held in the tool end by a number of different methods. A common one is to drill a hole in the end of the steel holder and to peen over the edges so as to hold the diamond. In another instance the end of the tool holder is drilled and then slit into quarters, the prongs thus formed being pressed down on to the diamond; the spaces between the diamond and the tool end are then filled in with solder or brazing metal so as to afford a rigid setting.

Fig. 153* illustrates a number of typical diamond tool shapes for different machining purposes.

* *The Machinist.*

The normal face angle α (Fig. 154) is usually made 10°, β being about 2°. On very hard materials β may be increased to 5° for turning tools. For boring tools β may be from 5° to 8° dependent upon the size of hole to be bored.
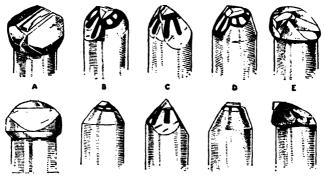
FIG. 153. DIAMOND MACHINING TOOLS

A = special form radius tool; *B* = normal turning tool; *C* = combined turning and facing tool; *D* = normal boring tool; *E* = combined boring and facing tool.

For *coarse turning purposes* the angle β is made larger and for finishing purposes it is smaller by tilting the tool around; for a high degree of finish or polish this angle is practically zero, and the tool set above centre so that the clearance face of the angle β portion is practically tangential to the work. A still higher degree of polish is obtained by rotating the tool so that its cutting edge is higher than the trailing edge; this angle may be as high as 45° for soft metals.
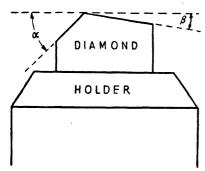
FIG. 154. DIAMOND TOOL ANGLES

Diamond tools require very rigid anchorage since they will not operate efficiently under vibration conditions, although the diamond will cut quite well at relatively high machining temperatures; provision should, however, be made for conducting the frictional heat away. In this connection both air- and water-cooled tool holders are now employed for special operations.

In regard *to machining speeds*, for normal purposes, speeds up to about 1000 ft. per min. are employable with feeds of 0·001 to 0·003 in. per revolution, with a depth of cut of 0·015 to 0·025 in. for roughing cuts and 0·004 to 0·010 in. for finishing. 'The speed selected depends

somewhat upon the nature of the material to be cut, although for metals ranging from the soft whitemetals to phosphor bronze practically the same speeds and feeds are used. It is possible to bore holes with diamond tools to within 0·0001 in. with excellent surface finish.

Another common application of diamond tools is for *turning long cylinders* of hard or abrasive materials such as hard rubber and synthetic resin; with alloy tool-steels the cutting edges would become blunter and a tapered effect obtained under similar conditions. The hard rubber rolls of typewriters are diamond turned in this manner.

Diamond dies for wire drawing are now widely employed. For this purpose the rough diamond is set into a brass die holder and held, temporarily, in place with shellac, whilst a conical centre for the drawing hole is being cut. The diamond is then brazed in the die holder. The surface of the brass holder is ground to smooth off the brazing so that the die will present a flat surface from which it may be located on the surface plate of a lathe while the drawing hole is being made. The die is then centred and held on the lathe face plate with shellac. The tool used to produce the hole in the die is an ordinary sewing machine needle: this is chucked in the end of the lathe tool holder and supported in the tail stock. The needle is charged with a thin paste made of *diamond dust* and oil. The diamond is rotated in the lathe and a reciprocating motion given to the needle so as to move it in and out of the hole being "ground" in the die.

The final hole thus made is enlarged at both ends to a slight curve for leading in the wire to be drawn down.

The wire is passed through from the large end of this hole. In this way it is possible to draw the wire down to within 0·0001 in. of the required size. Many tons of wire can be drawn through a die before any appreciable increase in diameter is noted.

Diamond dust is used to impregnate wheels employed for grinding tungsten carbide and similar cutting tools. It is also used in paste form with oil to charge the ends of copper and brass rods or tubes for drilling glass.

Felt

Felt is a material composed of wool, or wool and cotton, in a more or less compressed condition, the former being known as the "all-wool," and the latter as the "cotton-mixed" felt. The quality of the felt depends upon the ingredients, and the purpose for which it is required.

There is a number of grades of wool used in felts, which may be roughly classified as follows.

(1) Fine Wool, such as Virginia stock, long or short fibre, straight and kinky.

(2) Coarse Wool, such as Virginia stock, long or short, but usually straight and with little kink in it.

(3) Wool Shoddies, from old scrap wool felt or various wool fabrics; these have less length of staple or fibre than Virginia stock, and are used in the cheaper grades of felt, more particularly in cotton mixed felts.

For hard felt, it is necessary to use practically all wool, as cotton cannot be hardened in the felting or fulling process.

When cotton is used with wool shoddies, it is necessary to use glue sizing in order to make the felt hard, but glue-sized felts are not, in general, very satisfactory.

There is a variety of different felts upon the market, and the quality of these varies considerably, so that it becomes necessary to devise certain standard characteristics, such as the composition, density and hardness, for felts for special purposes.

It is possible to employ a hardness testing instrument of the scleroscope type, using a special scale, in order to determine the hardness of felt; the hardness property affords an accurate and convenient means for estimating the quality. It is also necessary to specify the percentage of wool and cotton, and to limit the amount of foreign matter, such as dirt or grit.

In some respects, felt, in its cushioning effects, resembles cork in the action of the imprisoned air and elastic fibres.

Felt is used in engineering work to eliminate noise and vibration, and for heat-resisting coverings; it is also used in the form of pads and wicks for lubricating purposes.

Felt washers and packings are widely used in automobile work for preventing oil leakage from engine bearings, gear-box and differential housings, etc.

In aeronautical work, felt has been used for packings and vibrationless fittings, such as for insulating instruments and instrument boards from the vibration of the engine, for lining metal clamping bands for the fuel tanks, lockers, camera boxes, and similar noise and vibration eliminating purposes.

A more recent application, of interest during the 1939 War on account of rubber conservation needs, is that of parts made of felt surrounded by an outer casing, or "corral," of rubber. The product, known as *Relt*, is from 30 to 70 times lighter than rubber, and possesses a wider possible variation of resilience than can be obtained from the usual rubber mouldings. Numerous shapes can be made in Relt.

Ferodo*

Ferodo is the name given to a group of materials having high frictional qualities, and which are used for brake-linings, friction clutches, discs and similar purposes.

Ferodo is normally supplied in two principal forms, namely, the cotton-bonded and the brass-wire woven asbestos varieties.

The cotton-bonded type is made of compressed cotton fibre impregnated with a special fluid, and it gives a higher coefficient of friction than the asbestos variety, but does not withstand such high temperatures.

The asbestos type consists of impregnated compressed asbestos, with numerous fine brass wires running through it. The object of the wires is to hold the material together and to conduct away the heat generated by the friction.

These materials possess high coefficients of friction and retain a fairly high value over considerable ranges of pressure, temperature and speed. Certain grades are also only slightly affected, in frictional properties, by water and oil.

The asbestos variety will withstand high temperatures, which would rapidly char leather, without much diminution in the friction coefficient.

The value of the coefficient depends a little upon the pressure, temperature and speed, and for the bonded asbestos type varies from 0·25 to 0·35, when in contact with cast iron or steel.

Temperatures as high as 200° C., pressures of 100 lb. per sq. in., and rubbing velocities of 6000 ft. per min., can be employed with this material; the coefficient of friction does not differ appreciably from the value of 0·30 under these conditions.

The value of the coefficient for the cotton fibre varies from 0·4 to 0·65; for pressures of 50 to 80 lb. per sq. in., temperatures of 100° C. and rubbing velocities of 2000 ft. per min., the value is 0·42 to 0·46.

The coefficient of friction is higher for the cotton fibre type, and its value increases with the temperature up to the charring point at 150° C. to 180° C.

For low pressures (10 to 20 lb. per sq. in.) and ordinary temperatures, the value of the coefficient varies from 0·2 to 0·3.

The effect of lubrication (mineral oil) is to lower the value of the coefficient to 0·05 to 0·2 in the case of the asbestos variety and to 0·2 to 0·3 in the case of the cotton type.

The cotton variety shows an extremely low rate of wear and many

* Manufactured by the Herbert Frood Co. Ltd.

motor bus brakes lined with this material have run for 20,000 miles without appreciable wear.

The amount of energy absorbed by a good brake lining varies from 100,000 to 120,000 ft.-lb. per sq. in. per min., for pressures varying from 50 to 80 lb. per sq. in., and coefficient of from 0·3 to 0·5 (in the dry state).

These materials are much used for lining the brakes of automobiles and motor cycles, winding engines, cranes and similar purposes, for the clutches of cars, and for friction drives of all kinds, etc.

Fibre

Vulcanized or red fibre is a hard, dense material composed of paper or cellulose made from cotton rag stock, together with zinc chloride and colouring matter, either aniline dyes or pigments.

The material is made in the form of a number of paper-like laminae, pressed together in the wet state under very great pressure, followed by slow drying, which is accompanied by a contraction in volume.

There are two prime operations in the making of vulcanized fibre. One is the manufacture of a thin unsized cotton paper and the other is the conversion of this paper into the finished product.

The paper is made from cotton rags that normally come to the fibre manufacturer from all parts of the world, principally Europe. The stock passes through several foreign material extraction processes before being made into thin absorbent paper on a Fourdrinier paper-making machine.

In the second general phase of manufacture, that is, the conversion of paper into vulcanized fibre, the paper is passed through a solvent that hydrolizes or parchmentizes a certain percentage of the individual fibres. The action of the solvent reduces these fibres to a gelatinous mass. The paper is then wound on a drum about 5 ft. in diameter, layers of the solvent-saturated paper being superimposed upon each other until the proper thickness is reached. The solvent, having performed its function, is then removed. When the sheet is finally "pure" or free from solvent, it is placed in a kiln and dried. As the water is driven off, the sheet shrinks to a hard, dense mass. At this point the fibre is just as hard and dense as it will ever be, but the sheet is wrinkled and distorted in much the same manner as leather becomes wrinkled when it is wet and dried. To straighten the sheets, they are placed under heated hydraulic presses and come out flat and smooth.

Vulcanized fibre tubes are made by winding the saturated paper on mandrels, then removing the solvent in the same manner as that described for sheets. The wet tubes are dried on rolling mandrels,

after which they are passed through rolling mills and brought to size. Rods are made by sawing sheets into square bars and turning these into round rods on special rod turning machines.

Properties of Fibre. Fibre is much used as an electrical insulating material, although its resistivity is fairly low for dielectrics, being of the order of 10^7 to 10^{10} ohms-centimetres. Certain hard dry varieties, however, have a resistivity of 7×10^{13} ohms-centimetres.

The dielectric strength of thicknesses varying from $\frac{1}{8}$ in. to 1 in. is given by Parshall and Hobart as 10,000 volts, and by Hendricks as 200 volts per mil at thicknesses of 50 to 150 mils, 160 volts per mil at a thickness of 0·4 in., 100 volts per mil at 0·7 in., and 90 volts per mil at 1·0 in.

The specific gravity of fibre varies from 1·0 to 1·5, according to the grade, average samples being about 1·4.

The tensile strength varies from 10,000 to 20,000 lb. per sq. in., and the compressive strength from 35,000 to 60,000 lb. per sq. in.

Fibre is naturally hygroscopic for this reason, and in the presence of moisture swells again, but, not being isotropic, it swells unequally in the different directions.

Applications. This material has been used for the fibre bushes of magnetos, and when used the material was arranged to swell axially, so that there was practically no risk of jamming the contact-breaker lever; fibre has since been replaced by other non-hygroscopic materials.

Fibre is used for a variety of purposes in the form of paper, sheet, slabs, tubes, etc.

Due to the tendency of the cotton fibres, when the stock is run on the paper-making machine, to arrange themselves longitudinally with the machine direction, the finished material has a distinct grain running lengthwise in the sheet. It is, therefore, well for the user of fibre to keep this in mind when the material is to be subjected to a bending operation. It will bend more easily with the grain than across the grain. It also follows that holes near the edge of a piece should be placed, for the greatest strength, near the cut edge, that is, parallel to the grain.
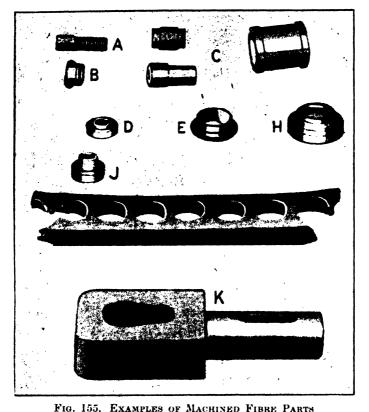
Fibre tubing is employed for carrying the high-tension leads of car or aircraft engines.

Fibre is supplied commercially in a number of grades and varieties, known by various trade names, such as red-fibre, hard-fibre, horn-fibre, leatheroid, fish-paper, indurated-fibre, waterproof-fibre, etc.

When the fibre-pulp is treated with Bakelite, a material is obtained having a much higher resistivity ($1·1 \times 10^{13}$ ohms-centimetres) and

non-hygroscopic; this material, which is known as "Bakelite-dielectro," is a hard, tough substance which cannot be moulded, but is impervious to hot water, oils and ordinary solvents.

Fibre has been employed for brake blocks, more especially for small machinery and cycles, but it is inferior both in frictional and wearing

FIG. 155. EXAMPLES OF MACHINED FIBRE PARTS

A and *B* = screwed parts; *C* = cylinders made by upset or drawing processes; *D, E, H, J* = parts made by punching and turning; *K* = a more elaborate article made by punching and turning.

qualities to the asbestos and other bonded brake materials, such as Ferodo. The coefficient of friction varies from 0·3 to 0·4, and the charring temperature from 150° C. to 200° C. Oil reduces the coefficient very considerably.

Fibre is now being replaced to a large extent by plastic materials. *Machining Hard Fibre.* Vulcanized fibre may be punched, stamped,

turned, sawn, milled, bored, in fact, it may be machined in any manner in which it is possible to machine metal.

The tools used for machining hard fibre and Bakelite appear to lose their edges fairly quickly, and for this reason the diamond-pointed tool previously mentioned is replacing tool-steels. When the latter are used the turning speeds should be from 600 to 800 ft. per min., the tools being ground to the same shapes, rakes, and clearances as for brass; no top rake is given in this case.

For sawing hard fibre circular metal-cutting saws running at about 3000 r.p.m. for 12 in. diameter saws are recommended. Threads can be cut on fibre rods with satisfactory results, using the same dies and cutting speeds as for brass; automatic screwing machines are now used for this purpose.

In punching fibre it should be remembered that a different allowance for "spring" must be made from that for metals, since the fibre closes in after the hole has been punched; for this reason the punch must be made rather *larger* than the hole to be punched. The usual allowance is about $\frac{5}{1000}$ in. for a 1 in. diameter hole.

When fibre discs have to be punched out it is necessary to reverse the allowance as the material actually opens out to the extent of about $\frac{5}{1000}$ in. per 1 in. diameter. The punch must, therefore, be made *smaller* than the disc required.

Gasket Materials

There are three main types of gaskets used in automobiles and on aircraft engines, namely, (1) for high temperature applications such as cylinder-head joints and for inlet and exhaust manifold and pipe joints, (2) for medium temperature joints such as valve and rocker-arm cover joints, water-pump timing gear and oil-sump joints, etc., (3) for low temperature joints, such as fuel pump, gear-box and back axle cover ones. For high temperature joints compressed asbestos, with or without wire gauge reinforcement, is generally employed, as for inlet manifolds and exhaust joints. For cylinder-head joints the most widely used form of gasket is the copper-asbestos one having two outer thin soft copper layers with asbestos between; these gaskets are made to the exact shape of the cylinder-head joint, the holes for the studs, cylinder bores and water connections being punched out, and all edges are generally sealed with the thin copper sheet, so that no asbestos is exposed.

Owing, however, to the somewhat yielding nature of this type of gasket, the compression ratio of any group of cylinders is liable to vary according to the degree of tightening of the cylinder-head nuts.

For this reason gaskets of plain thin copper and other metals have been substituted in certain recent engines. These solid metal gaskets are coated on either side with a jointing compound which effectively seals any slight inequalities in the surfaces of the joints when the engine attains its working temperature.

A type of cylinder-head gasket used in Germany since 1939, owing to supplies of asbestos being very limited, employs the synthetic rubber material known as Buna. It consists of three sheets of Buna and two layers of fine steel wire netting, the wires of the two layers being placed at angles of 45 degrees with each other. The wire netting and rubber sheets are vulcanized together. Unlike natural rubber, which softens when exposed to high temperatures, Buna has a tendency to "tighten." Owing to the elastic nature of the rubber and the fact that the gasket is not coated with graphite, it is said to have better holding properties than conventional gaskets. The new gaskets are claimed to be resistant to hot water and hot oil up to 180° C.; also to glycol and leaded petrol.

For exhaust manifold joints compressed asbestos with a suitable high temperature resistant binder is usually employed, although copper asbestos gaskets are also used for this purpose. When asbestos gaskets are employed they are stamped or cut to shape from sheet material coated with graphite upon both faces.

For medium temperature purposes compressed asbestos and rubber-coated asbestos sheet are favoured. More recently synthetic rubbers have been introduced for such applications. Thus in one typical example the gasket is made by first blanking it from asbestos sheet and coating with the synthetic rubber Neoprene cement. Another type is made by compressing the asbestos-Neoprene product.

These gaskets are suitable for use on valve cover joints, rocker-arm covers, but not cylinder-head joints. They will withstand the effects of oil, steam, water, glycerine, ethylene glycol, etc., at temperatures up to 200° C., and have a tensile strength of 1000 lb. per sq. in.

For joints that are not exposed to temperatures above about 100° C., compressed cork sheet and rubberized fabric are frequently employed. The covers of automobile headlamps are usually provided with compressed cork ring joints backed with fabric for strength purposes; this is a necessary precaution since the cork possesses very little tensile strength.

Another type of engine gasket material introduced more recently by the Chrysler Corporation of America consists of a synthetic rubber composition known as Ligno-Neoprene; it is used largely as a substitute for cork gaskets. In all, three different grades are employed by

this firm, namely, (1) metallic asbestos gaskets for high temperatures and pressures, e.g. cylinder-head joints; (2) synthetic rubber Thiokol paper gaskets for sealing at low compression; and (3) synthetic rubber composition gaskets, namely, Ligno-Neoprene for joints where a good sealing combined with a certain amount of resiliency are required.

Corrugated cupro-nickel sheet gaskets* are now widely used for internal combustion engine and steam joints subjected to high pressures and temperatures. This type of gasket is highly resistant to corrosion and the corrugations seal any surface irregularities.

Glass

Glass is made from (a) silica, (b) salts of alkali metals, and (c) salts of bases other than alkalis, as follows—

(a) Sand or felspar.

(b) Sodium sulphate, or carbonate, or potassium carbonate.

(c) Red lead, limestone, chalk, barium carbonate, magnesium carbonate, zinc oxide, alumina, etc.

In general, glasses rich in silica and lime are hard, whilst those containing much alkali, lead, or barium are soft.

The following are typical analyses† of different glasses—

VERRE DUR GLASS. Silica (SiO_2) 71 per cent, sodium oxide (Na_2O) 12 per cent, potassium oxide (K_2O) $\frac{1}{2}$ per cent, calcium oxide 14 per cent, aluminium oxide (Al_2O_3) and magnesium oxide (MgO) 2 per cent.

JENA GLASS. Silica 72 per cent, boron oxide (B_2O_3) 12 per cent, sodium oxide (Na_2O) 11 per cent, aluminium oxide (Al_2O_3) 5 per cent.

The silica content ranges from 50 to 75 per cent in the different glasses.

FLINT GLASS is a dense glass which contains lead and possesses a high refractive index and dispersive power; it is used for lenses of telescopes, microscopes, and optical instruments.

CROWN GLASS was the name usually applied to lime-silicate glass, but it is now employed for glasses of low dispersive power.

It is not proposed to go into the optical or thermal properties of glasses here, for full information of which the reader is referred to works upon optics and heat.

Glass is hard and brittle, its tensile strength varying from 2000 to 10,000 lb. per sq. in., according to the quality, and its compression strength from 13,000 to 40,000 lb. per sq. in.

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* See Fig. 105, page 214.

† *Physical and Chemical Constants*, G. W. C. Kaye and T. H. Laby. (Longmans, Green & Co.)

The following results were obtained from tests upon different kinds of glass bars, plates, cylinders, and cubes.

TABLE 109

MECHANICAL PROPERTIES OF DIFFERENT KINDS
OF GLASS

Name of Glass	Form in which Tested	Mean Specific Gravity	Mean Tensile Strength in pounds per sq. in.	Mean Compressive Strength in pounds per sq. in.
Best flint glass .	¼ in. diameter bars .	—	2413	..
	Thin plates . .	3·078	4200	——
	Cylinders ⅜ in. dia.	——	—	27582
	Cubes 1 in. side .	...	——	13130
Common green glass	Bars . . .	——	2896	——
	Thin plates . .	2·528	4800	——
	Cylinders . .	. .	——	39876
	Cubes . . .	—	—	20206
Extra white crown glass	Bars . . .	——	2546	..
	Thin plates . .	2·450	6000	——
	Cylinders . .	——	—	31003
	Cubes . . .	...	..	21867

[Kent]

The value of the elastic modulus for glass is about 4300 to 5000 tons per sq. in. for Jena crown glass and 3400 to 3700 tons per sq. in. for the Jena flint variety.

The moduli of rigidity are from 1700 to 2500 and 1500 to 1800 tons per sq. in. respectively, and the corresponding values of Poisson's ratio 0·20 to 0·27 for crown and 0·22 to 0·26 for flint glass.

The specific gravity of crown glass varies from 2·20 for the silicate crown variety up to 3·60 for the heavy barium crown type; for the silicate flint variety it is about 3·5, for the borosilicate flint 2·85, for the barium flint 3·95, and for heavy flint glass 5·0 to 5·9.

The coefficient of linear expansion of typical soda glass is 0·0000085 ; flint glass, 0·0000078 ; Jena glass, 0·0000060 to 0·0000075 ; lead glass, 0·0000095, and Pyrex, 0·000003.

The thermal conductivity of soda glass is about 1·3 to 1·8 × 10⁻³ (C.G.S. units), of flint glass 2 × 10⁻³, and crown window glass 2·5 × 10⁻³.

The insulating properties of glass are well known, the resistivity being of the order of 10^{11} to 10^{16} ohms-centimetres at ordinary temperatures, but decreasing rapidly as the temperature increases. Potash glass has a higher resistivity than soda glass, and annealing increases the resistivity. Moisture condenses on the surface of glass and destroys its electrical insulating properties, due to surface leakage.

The dielectric constant varies from 5·5 to 10, and the dielectric strength from 150 to 300 volts per mil.

Safety or Unsplinterable Glass. There are several patented processes for rendering glass unsplinterable, amongst which may be mentioned the method, used for the glass of factory buildings, houses and ships,
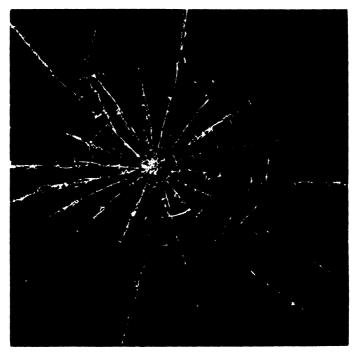
FIG. 156. FRACTURE OF A GOOD SAMPLE OF UNSPLINTERABLE GLASS, GIVING CHARACTERISTIC SPIDER WEB APPEARANCE
(Murray & Spencer)

of casting or running molten glass around flat wire netting of fairly small mesh, so that the resulting sheets contain the wire netting in about their central planes.

With the increasing use of automobiles there has been a growing demand for a grade of glass that does not shatter into splinters when it receives a violent blow; in this respect a large number of injuries incurred in motor accidents are due to the fracture of the ordinary glass windscreens and windows; the use of safety glass in automobiles is now a compulsory legal obligation.

It is commonly made by placing a sheet of celluloid, cellulose acetate, or some similar transparent material between two plates of glass. The surface of the material forming the intermediate layer is treated so as to cause adhesion between it and the glass. In addition, the inner surfaces of the glass are sometimes coated with a suitable
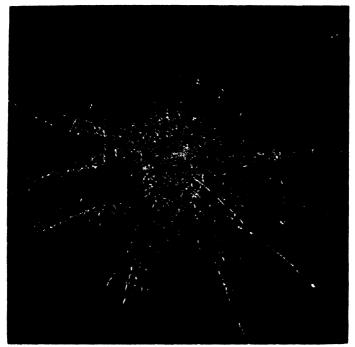
FIG. 157. GOOD SAMPLE AFTER UNDERGOING PENETRATION TEST
[ONLY FINELY POWDERED GLASS HAS BEEN DETACHED]
(*Murray & Spencer*)

material in order to increase their adhesion. Generally, the intermediate layer is treated with a liquid immediately before mounting between the glass plates, pressure being afterwards employed.

One of the difficulties in safety glass manufacture is to obtain good adhesion between the glass and intermediate layers. In this respect some unsatisfactory grades of so-called safety glass have been fitted to motor cars; these after a few months' service have shown discoloration of the intermediate layer, and in many cases separation. The result of the latter defect is a mica-like appearance that detracts from the transparent properties of the glass. The worst feature of such

glass is the splinterable property which usually renders it no better than ordinary glass.

If the active solvent at the junction is in excess there is a diffusion into the intermediate layer so that it becomes softened and the glass loses its mechanical strength; the glass is then liable to fracture under

FIG. 158. APPEARANCE OF A POOR SAMPLE AFTER PENETRATION TEST, DURING WHICH LARGE FRAGMENTS OF GLASS HAVE BEEN DETACHED

(*Murray & Spencer*)

small impacts or shocks. If the intermediate layer is too soft the glass will shatter under the action of a violent blow, and detached pieces will fly back from the point of impact. Similarly, if the intermediate layer is too brittle the non-splinterable properties will suffer. Safety glasses should be subjected to impact tests such as the falling weight one, and should further be given a prolonged testing under vibration conditions similar to those experienced in service on automobiles. The former tests will reveal the non-splinterable qualities of the glass, and the latter its resistance to separation of the layers.

Murray and Spencer* have devised a testing machine of the falling weight impact type for testing specimens of safety glass. The height and weight of the striker can be varied in order to produce blows of considerable impact value to emulate those occurring in motor-car accidents. Specimens fractured with this machine are examined carefully, and from the nature of the fracture an idea of their relative qualities can be obtained. The results of some tests are shown in Figs. 156, 157, and 158.

Other tests specified for safety glass include : (1) *Fracturing test* with blows of increasing intensity until fracture occurs. (2) *Bursting test* on samples 12 in. square. (3) *Heating test* on a sample heated to 100° C. to 105° C. for 24 hours, after which it is examined for freedom from bubbles and change of colour, a Lovibond Tintometer being used for the latter purpose. (4) *Coloration test* based on exposure to intense ultra-violet rays from an electric arc. (5) *Edge-sealing test* on sample placed in a water-bath at 60° C., with the edges normally sealed.

This material is widely used for the windscreens of cars, for goggle-glasses, bulkhead door illuminators, port-holes, periscopes of submarines, observation windows for armoured cars, field glasses, and even for spectacles. More recently glass has been superseded in aircraft by transparent synthetics such as Perspex, Lucite, etc.

In thicknesses of from 1 to 2 in., safety glasses are bullet-proof at ordinary ranges ; the effect of the impact of a bullet, in the case of the smaller sizes is to punch a clean hole, with short radiating cracks around it.

Another kind of toughened glass that has been used for automobile windscreens is of uniform structure resembling plate glass. It is of special composition and heat-treated during manufacture so that upon impact the glass cracks into innumerable tiny fragments. does not splinter off, but breaks into harmless crystals. The windscreen, however, becomes obscured so that the driver is unable to see clearly through it.

Glass Insulating Tape and Cloth

Tape and cloth woven from fine glass thread are now employed for electrical insulating purposes. The fibres can be made to a very small diameter ; in some cases as fine as one-fifteenth the diameter of the average human hair. The woven products resemble ordinary textiles and, being very flexible, are suitable for the insulation of coils for electric motors, dynamos, transformers and other electrical machines

* "Testing Safety Glass," H. D. Murray and D. A. Spencer, *Indust. Chem.* (October, 1930).

as well as for cables. They have the well-known insulating properties of glass and are chemically resistant to most corrosive influences. They will withstand high temperatures without losing their insulating properties—a quality not common to most other insulating materials. Further, they can be treated with insulating varnishes for the purpose of building up insulation around metal conductors. Being impervious to moisture and possessing high dielectric strength these glass-woven products have definite advantages over most other insulating materials; moreover, they are relatively inexpensive.

A typical example of a commercial glass cloth used in electrical work is that of Fiberglas.* It consists of glass cloth woven from continuous fibre soda-free yarn, impregnated with heat-resisting insulating varnishes.

It is particularly suited to electrical insulation requirements and is supplied in various thicknesses coated with black or yellow insulating varnishes; also in standard tape widths and standard roll lengths. It is claimed that electrical apparatus insulated with Fiberglas has greater overload capacity, can be made smaller in size and lighter in weight and will outlast equipment protected with ordinary insulating materials.

Gutta-percha

Gutta-percha is the name given to certain varieties of gum, similar to those from which rubber is derived, the best qualities of which are obtained from the Isonda gutta-tree, which grows in Borneo, Sumatra and Malacca. The gum *Balata*, which is similar to gutta-percha, is derived from trees in Venezuela.

Gutta-percha is produced from the latex or gum in the same manner as rubber, but it is generally used in the pure state, and is not usually vulcanized, pigmented, or filled.

The density of gutta-percha varies from 0·97 to 0·98, and its electrical resistivity is about 34×10^9 ohms-centimetres, the apparent dielectric constant being 2·86.

Gutta-percha is much used for insulation purposes, i.e. for covering submarine cables, splices and joints.

Insulating Tape

This material, which is also known as rubber-treated or adhesive tape, consists of fabric tape (linen or cotton) impregnated with plastic or sticky gum, the base of which is rubber gum. Fillers and bituminous

* Made by the Irving Company of New Jersey, U.S.A.

substances are used to adulterate the gum; the best grades contain the more expensive rubber gums.

The impregnated fabric possesses fair electrical insulating properties, and when slightly warmed can be made to adhere to itself and to metal, wood and other surfaces.

It is much used for electrical repair work, temporary lead insulations, as a temporary means of preventing air leaks in pipes, preventing nuts and other parts shaking loose, preventing rattle of adjacent parts on automobiles and aircraft, stiffening laminated springs, etc.

Leather

Leather is derived from the hides of domestic animals by tanning processes.

It is much used in engineering work for driving belts, friction lining material, washers for hydraulic work, cocks and taps, etc.

The specific gravity of leather is from 0·90 to 0·98, a cubic foot weighing about 57 to 60 lb. on the average.

The tensile strength of single, ordinary (oak) tanned leather belting varies from 3000 to 6000 lb. per sq. in., for Helvetia single leather from 5500 to 6000 lb. per sq. in.; for double, ordinary tanned leather 2000 to 3600 lb. per sq. in., for double Helvetia leather 4000 to 5500 lb. per sq. in. Mineral-tanned belting gives from 4000 to 7000 lb. per sq. in.

The horse-power transmitted by a leather belt, per inch width, is given by the following relation:—

$$\text{h.p.} = \frac{T \cdot V}{33,000}$$

where T = difference between the tensions on the driving and free side of the belt in lb., and V = belt speed in feet per min.

The working stresses vary from about 40 lb. per inch width for ordinary single belts to about 90 lb. for heavy double belts.

The British Standard Specification B.S. 424 requires a minimum strength of 2500 lb. per sq. in. for splices in oak-tanned leather belting.

The coefficient of friction of leather is high for low pressures, the value varying from 0·4 to 0·5 for temperatures below 30° C. and for pressures lower than 20 lb. per sq. in. and on cast-iron surfaces.

Linseed Oil

Linseed oil is a vegetable oil obtained from the seeds of flax, and it is widely used as a constituent of paints and varnishes.

It has a specific gravity of 0·932 to 0·936 at 15° C.

Boiled linseed oil, when exposed to ordinary atmospheric conditions, becomes oxidized into a viscous or hard film; this effect is accelerated by the action of heat, or drying agents.

The raw linseed oil is chiefly used with white lead colours, and the boiled variety (which tends to darken paints) with dark colours, such as reds, greens, browns, blues and black pigments.

The method of obtaining boiled linseed oil* is to add to each gallon of raw oil about 6 oz. of litharge and 2 oz. of red lead, and to heat for a few hours at about 120° C. to 200° C., afterwards running off the clear oil when cold.

The drying quality of linseed oil is usually tested by painting a piece of glass and exposing to a temperature of 38° C., noting the time required to dry.

Linseed oil is widely employed in oil varnishes, with soluble gums, such as amber, copal and gum animi; these varnishes take a much longer time to dry than the spirit varieties, but give more elastic, harder, and more durable results.

The name *linoxyn*, or *oil-rubber*, is given to the rubbery material formed by the oxidation of linseed oil. It is sometimes used for so-called "artificial" rubbers, with other filling ingredients.

Mica

Mica is a refractory material, being a double silicate of alumina, or magnesia, and potash or soda; it contains various impurities such as iron, which gives it a grey or black foliated appearance, magnesia, which tends to darken it, and aluminium silicate, which helps to render it more transparent.

Mica is obtained in the form of laminated sheets, which can be readily split into thin sheets as small as 0·006 mm. in thickness. The best grades of mica come from India and Canada, the American or domestic grades coming last.

White or Muscovite mica is much used for electric and other heating apparatus; transparent lamp and gas chimneys and panels in oil and gas stoves are made of white mica.

The largest commercial sizes of cut mica sheets are about 8 or 10 in. sq. or 10 × 8 in., and are much more expensive compared with smaller sizes, so that it is now usual to employ for electrical purposes, where possible, moulded or built-up mica sheets made from small flakes or ground mica, known under various commercial names, such as Micanite, Mica-paper, Mica-cloth, Megomic, etc.

Pure mica is one of the best electrical insulating materials known,

* The oil is not "boiled" in the real sense of the word.

as it not only possesses a very high resistivity but also is capable of withstanding high temperatures.

The resistivity of mica varies with the grade or source of origin, but the following values* represent the more reliable results—

TABLE 110

ELECTRICAL PROPERTIES OF MICA

Source	Resistivity in Ohm-centimetres ($\times 10^{12}$)	Dielectric Constant	Disruptive Strength in Volts per Millimetre
Bengal	15-133	2·5-5·5	50,000-80,000
Madras	7-118	2·8-4·7	40,000-120,000
Canada	0·44-22	2·9-3·0	80,000
South America	39	5·9	40,000-90,000

For ordinary electrical design purposes the volume resistivity is taken as 4×10^{13} to 2×10^{17}, the latter figure being for clear and the former for ruby mica.

The surface resistivity at 75 per cent humidity is from 6×10^8 to 1×10^{11}, the limits being for the two varieties previously mentioned.

The electric strength varies from 2000 to 6000 volts per mil according to the thickness, the higher value being for the best sheets 1 mil thick. The power factor of the Muscovite micas is less than for the amber micas; thus for clear Muscovite mica the power factor may be as low as 0·003. For clear amber and silver amber micas the power factors are 0·02 and 0·05 respectively.

The specific gravity of mica is about 2·7 to 3·2.

Its specific heat varies from 0·206 to 0·208.

The thermal resistivity varies from 180° C. to 250° C. per watt per cm. cube.

The melting point of mica is 1200° C. to 1300° C.

The insulating properties of mica are retained up to 600° C. to 800° C., the effect of increasing temperature being to disintegrate the laminae into small flakes.

Amber mica, of Canadian origin, is less affected by heat than the other varieties, and is somewhat softer; it is used for the armatures of motors and dynamos. as it is not so hard as the domestic grades and

* Vide *Standard Handbook for Electrical Engineers* (McGraw Hill Book Co.). *Mica, Its History, Production, and Utilization*, H. Zeitler. *Mica*, Canadian Dept. of Mines Publication.

wears down at approximately the same rate as the copper segments so that hard mica ridges are not formed.

Condensers used for magnetos and high-frequency purposes employ the best clear ruby mica; sometimes, however, specially selected slightly stained mica is employed.

For heating and cooking where mechanical strength considerations are concerned the Muscovite micas are used; where great heat is required, as in an electric furnace, phlogopite is employed.

Micanite, made from thin pieces of mica into large sheets, using suitable adhesives, is cheaper than mica, but is inferior in electrical properties; moreover, it should not be used at higher temperatures nor under oil. Micanite commutator separators are made from Indian ruby splittings. Micanite is also available as hard boards, made by impregnating with special bonding media and baking under pressure. Moulding micanite is another variety for sheet material parts of special form. There are also several other forms of Micanite, including Mica-folium, Flexible Micanite, Reinforced Flexible Micanite and Heat-resisting Micanite.

Mica is used for numerous electrical purposes as an insulator; it is employed in the form of a series of washers, tightly clamped and turned to size, for the insulation of high-grade automobile and aero-plane sparking plugs.

Porcelain and Steatite

The grades of porcelain employed for electrical purposes contain silica, clay and felspar; the three felspars which are used comprise orthoclase (or potash felspar), albite or indianite (or soda felspar), and anorthite (or lime felspar).

The clays employed are china clay or kaolin and ball clay.

The following is a standard composition—

Quartz	.	.	30 per cent
Kaolin	.	.	50 ,,
Felspar	.	.	20 ,,

The felspar acts as a flux and tends to unite the other constituents when fused.

Porcelain may be made either by the *dry process*, in which the ingredients are mixed and moulded under hydraulic pressure and then "fired" in the usual way, or by the *wet process*, in which the materials are mixed with water, into a wet plastic cake, moulded or worked to shape, dried, and, after dipping in the glazing bath, placed in the kiln before "firing." Most electrical porcelains are made by the wet process.

The glazing mixture contains more flux than the porcelain mixture, so that it vitrifies at a lower temperature. The shrinkage during manufacture, from the clay, amounts to from 10 to 20 per cent.

Dry process porcelain is usually porous and is not suitable for high voltages.

Electrical porcelain has a specific gravity of from 2·5 to 3·5. It is not affected by oils, acids, alkalis or water, and it should not be porous in the unglazed condition.

The coefficient of linear expansion varies from 2·5 to 5·5 × 10⁻⁶ per degree C.

The specific heat is 0·17 to 0·25 (0° to 1000° C.) and the thermal conductivity is 2·5 × 10⁻³ C.G.S. units.

The electrical resistivity of unglazed porcelain is of the order of 10¹⁴ to 10¹⁵ ohms per cm.³ at ordinary temperatures, but decreases fairly rapidly with temperature increase. At high temperatures it becomes a conductor, so that it is not suitable for electrical furnaces.

The dielectric constant is from 4·4 to 6·8, and at low frequencies the disruptive voltage is about 30 kilovolts for a thickness of 0·1 in. and about 110 kilovolts for a thickness of 0·5 in.

Although not of the porcelain group, the low loss ceramic material known as *Steatite* has better electrical properties; it is, however, more expensive.

The following are typical properties: Specific gravity, 2·7. Electric strength at 50 c/s., 900–1150 volts/mil. Power factor (tan *d*) at 20° C.; 300 kc./s. — 0·0003; 50 mc./s. — 0·0005. Permittivity (*κ*), 5·5–6·5. Insulation resistance at 300° C., 3·2 × 10¹⁰ ohms/cm.³ Compressive strength, 140,000 lb. per sq. in.

European soft felspathic unglazed porcelains have a tensile strength of from 10,000 to 12,600 lb. per sq. in., and a compressive strength of about 65,000 lb. per sq. in.

The modulus of elasticity is about 2,500,000 lb. per sq. in.

Porcelain is widely used for electrical insulators, fuse-boxes, large and small switches, insulated handles, electrical connections, sparking plug body insulators, outside live wire insulators, etc.

Sparking Plug Insulators

The insulating materials used for modern sparking plugs of automobile and aircraft engines include mica, certain ceramic insulating materials and sintered aluminium oxide.

(1) *Mica*, whilst possessing excellent electrical insulation properties at the engine working temperatures and secondary circuit sparking voltage of 5000 to 8000, has certain disadvantages. Thus, it has a low

heat conductivity so that cooling of the plug is difficult, and it encourages the accumulation of current-conducting deposits such as burnt oil and fuel-origin carbon during the "idling" periods of operation. Further, if overheated the mica becomes dehydrated with consequent expansion and brittleness leading to the formation of a white

Steel
Corundite
'Sintox'
Insul?
Ni Steel
Cu Washers
Ph Br
Pt Inserts
Ni Ring

Steel
'Zircrund'
Insul?
Brass Collar
Ag
Fe Washer
Pt Ring
and Inserts

(A)   (B)   (C)
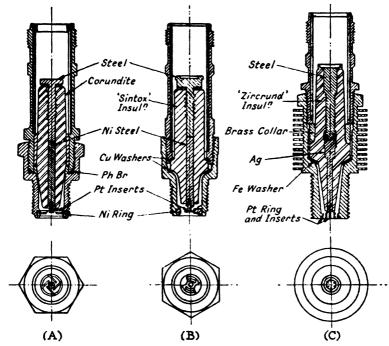
FIG. 159. AIRCRAFT SPARKING PLUGS WITH SINTERED
ALUMINIUM INSULATORS, SHOWING ALSO THE USE OF
NICKEL AND PLATINUM ELECTRODES
A —K.L.G. *B*—Lodge. *C*—Sphinx.
(*Journ. Roy. Aeron. Soc.*)

powdery substance. The thermal expansion of mica is about one-half that of the steel central electrode and shell, so that it is more difficult to maintain gas-tight joints. Mica has also an affinity for moisture which is a disadvantage for engine starting and slow running purposes.

Finally, when used with leaded fuels mica-insulated sparking plugs are exposed to attack by the lead products, the practical effects being evident as partial disintegration by pinholes punctured right through the mica to the electrode within.

For normal types of petrol engine the mica insulated plugs have

given satisfactory results in the past with ordinary petrols. The mica used for the exposed part of the insulator near the central electrode is usually of the clear ruby or Muscovite grade, made in the form of washers placed over the central electrode and tightened securely. The rest of the insulator is often in the form of mica wrappings around the electrode—since washers would provide potential leakage paths between the laminations from electrode to shell.

(2) *Ceramic Insulators.* These widely used materials include the porcelains and steatite, special grades being employed for aircraft engine sparking plugs. In the earlier ceramics quartz and felspar constituents were employed, but these were found to cause volume changes with impaired insulation efficiency at high temperatures and so they were replaced with the inert mineral known as *Sillimanite*— an anhydrous aluminium silicate product, both strong and tough, with a melting point of about 1810° C.

More recently improvements in ceramic insulators have been effected by employing much finer ground materials and higher production temperatures, the products being superior in mechanical and thermal properties and glaze fit. An advantage of ceramic insulators is their relative lightness as compared with mica : thus it is possible to make aircraft engine plugs of about one-third the weight of mica ones.

(3) *Sintered Aluminium Oxide.* This more recent insulating material consists of aluminium oxide sintered into a hard homogeneous substance having about five times the thermal conductivity of porcelain and twice its strength. Moreover, it is immune from attack by "leaded" fuels such as the high octane ones used in aircraft engines.

It possesses a thermal expansion coefficient nearer to that of nickel and steel than any of the ceramic insulators, and it is therefore easier to obtain gas-tight joints. A further advantage of this insulating material is the ease with which it can be cleaned ; even sand-blasting does not injure its surface. Certain initial difficulties in connection with the insulator joints and low insulation resistance due to carbon deposits when operating at low temperatures—as when the engine is "idling"—have now been overcome satisfactorily.

Sintox is a typical insulating material of the sintered aluminium oxide class ; a typical application of this material is given in Fig. 159.

ENGINEERING PLASTIC MATERIALS

THE methods of manufacture of articles, both metallic and non-metallic, used for engineering purposes, by direct machining processes have given way, in many cases, to those of casting or moulding.

The advantages of being able to obtain parts to the desired shapes and sizes by mass-production methods are obvious. In this respect particular mention must be made of the hot-stamping and die-casting methods, described in previous chapters, employed for many non-ferrous alloys; these give articles requiring practically no machining or finishing for most purposes.

In the case of certain organic or non-metallic materials used for parts hitherto made by lengthy and often complicated hand and machine processes from woods, the development of the moulding processes has resulted in millions of articles covering a wide range of shapes and sizes now being made at extremely low cost. Moreover, each of these parts can be made in large numbers, to exact dimensions and in materials very much harder, stronger, and more durable than woods.

In addition a variety of colour and surface effects, including various wood and metallic surface finishes, can be obtained with many of the synthetic materials in question.

The plastic materials that have been employed in engineering work include bitumen, natural resin, cellulose esters (cellulose acetate and nitrate), casein and resinoids or synthetic resins.

These and other materials employed for similar purposes may conveniently be grouped under two main headings, as follows: (1) *Thermo-plastic materials* and (2) *Thermo-setting materials.*

Thermo-plastic Materials

Thermo-plastic materials are the less permanent ones which soften under the application of heat (with or without pressure) and are hard when cool. Repeated heating and cooling does not in general affect their physical properties. The thermo-plastics include bitumen, casein, cellulose acetate, natural resins and certain more recent compounds, such as *polystyrol*, *polyvinyl*, and *methyl-methacrylate.*

Bitumen, the oldest known plastic, was employed about 3000 B.C. The bitumen plastics of to-day are used chiefly in the electrical industry

and are made from bituminous products by mixing with a suitable filler, such as slate dust or asbestos in powder form. These plastics can be moulded into various forms and have good electrical insulating properties. They have been used for battery-cell plugs, stoppers, electrical mouldings of the cheaper class, etc.

Casein is a precipitation product obtained from milk by the action of rennet or acid. The casein obtained is ground, coloured and moulded or extruded into rods, sheets or blocks. These are then hardened by treatment with a solution of formaldehyde. The casein product is not suitable for moulding into intricate forms as with the synthetic resins, but is used in the rod, sheet or block form to make articles by machining processes, e.g. sawing, turning, drilling, etc. It is slightly hygroscopic so that its uses are somewhat limited to articles such as handles, buttons, knobs and ornamentally-turned parts. Typical commercial casein plastics are Erinoid and Galalith. In connection with the production of casein it requires $3\frac{1}{4}$ gal. of skimmed milk to make 1 lb. of casein.

Cellulose acetate is a modern substitute for *celluloid* which is made by the treatment of cellulose nitrate with camphor. Unlike the latter material cellulose acetate is not highly inflammable, but merely burns at a slow rate, or chars. It is usually available in transparent sheet form, but can be obtained as a moulding powder; it is also supplied in the opaque form. *Celastoid* and *Cellastine* are typical cellulose acetate type plastic materials. The cellulose acetate plastics have good electrical insulation properties, a specific gravity of 1·25 to 1·55 and tensile strengths of $1\frac{1}{2}$ to $2\frac{1}{2}$ tons per sq. in.

Cellastine* is a cellulose acetate compound having a plastifying agent which renders it stable under normal conditions. It is supplied in rods and sheets, has good electrical and mechanical properties and is used for electrical and wireless parts where good insulation properties are desirable.

Breakdown electrical tests made on opaque and transparent Cellastine in oil at 20° C. showed that from 650/750 volts per mil were required for opaque colours of 0·060 in. thickness, and 840 for translucent ones of the same thickness.

Tests made on black Cellastine mouldings gave the following characteristics—

Specific gravity, 1·55.
Gross breaking strength, 4380 lb. per sq. in.
Breakdown value at 20° C. on a thickness of 88 mil., 636 volt/mil.

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* British Celanese Ltd., London.

Volume Resistivity—
   20° C., $1·5 \times 10^{12}$ ohms/cm. cube.
   57° C., $1·8 \times 10^{9}$ „   „   „

Surface Resistivity —
   20° C., $1·4 \times 10^{10}$ ohms/cm. sq.
   57° C., $5·4 \times 10^{7}$ „   „   „

Cellastine is employed for a variety of industrial purposes, apart from its engineering applications. The transparent Celastoid or Cellastine has been used for aeroplane windscreens. Some other applications include acoustic instruments, bathroom fittings (e.g. brackets), clock cases, coach and motor body building (for interior fitments, smoker's requisites, facia boards, and instrument dials), cutlery handles, cycle manufacture (Celastoid tubes are being used for covering frames, handlebars, pumps, and for chain cases), drawing instruments, as a glass substitute for steam gauges, motor goggles, indicators and lamp glasses (both transparent and coloured). It has another important use, namely, as the intermediate layer of *safety glass used for windscreens*, since, unlike celluloid, it does not discolour with prolonged exposure.

Polystyrols are thermo-plastics obtained by polymerization of the hydrocarbon styrene which is derived from ethylene. These materials are normally quite transparent, strong and of excellent electrical properties.

This material can also be obtained coloured. It has a specific gravity of 1·05 and a tensile strength of 5000 to 5500 lb. per sq. in. It is non-hygroscopic.

Polyvinyls are thermo-plastics derived from vinyl compounds such as vinyl chloride or acetate. They are obtainable in either the opaque or coloured condition. The specific gravity varies from 1·25 to 1·35 and tensile strength from 6000 to 8000 lb. per sq. in. The material is very slightly hygroscopic.

Methyl-methacrylates are among the recent thermo-plastics which are used for aircraft construction purposes, being transparent and strong. They have an important application for the windows, domes, windscreens and similar transparent parts of modern aircraft. Typical commercial plastics of this group include Perspex, Plexiglas, Lucite and Diakon.

The physical and mechanical properties of the principal kinds of thermo-plastic materials are given in Table 111.*

* "Plastic Moulding," G. Dring, *The Automobile Engineer*, April, 1938.

TABLE 111

PROPERTIES OF THERMO-PLASTIC MATERIALS

Properties	Vinyl chloride Acetate Resins Unfilled	Methyl Methacrylate Resin	Styrene Resin	Shellac Compound	Casein	Cellulose Acetate	Cellulose Nitrate
Compression ratio (bulk factor)	2·0	2·0	2·5	—	—	2-2·8	—
Specific gravity	1·34-1·36	1·18	1·05-1·07	1·1-2·7	1·35	1·27-1·63	1·35-1·60
Tensile strength in lb. per sq. in.	8,000-10,000	7,000-9,000	5,500-7,500	900-2,000	7,600	3,500-10,000	5,000-10,000
Modulus of elasticity, lb. per sq. in. × 10³	3·5-4·1	6	4·6-5·1	—	5·1-5·7	2-2	2·4
Compressive strength, lb. per sq. in.	—	8,000	13,000-13,500	—	—	11,000-16,000	—
Flexural strength in lb. per sq. in.	10,000-13,000	13,000-17,000	6,500-8,000	—	—	5,200-8,800	—
Impact strength. ft.-lb. (C-Charpy; I-Izod. N-Notched, U-Unnotched.)	0·3-0·6 I, N	0·25-0·5 C, N	0·16-0·25 I, N	—	1·0 I	3-12 C, N (per sq. in.)	3-12 C, N (per sq. in.)
Softening point (degrees C.)	130-160	170-235	110-200	150	200	145-260	160-195
Breakdown voltage. 60 cycles, volts per mil (instantaneous)	400-500	480	500-700	100-400	400-700	800-850	600-1,200
Power factor 10³ cycles	0·0143	—	0·0001	—	—	—	—
Water absorption, immersion 24 hours	0·05-0·15	0·3	0·00	—	3·7	1·4-2·8	1·0-3·0

Thermo-setting Plastic Materials

This important group of plastic materials includes those which soften or become plastic under the influence of heat (with or without pressure) and on continuous application of this heat (with or without pressure), or by pressure alone, set into hard compounds which cannot again be softened by heat application, i.e. are permanent in constitution.

The thermo-setting plastics include the phenol-formaldehyde and urea-formaldehyde products, the latter being the more recent ones.

The phenol-formaldehyde plastics are produced by the condensation of phenolic compounds with formaldehyde. Cresols act in the same way as the phenols but give different end products. The resulting *synthetic resin* may be utilized in powder form mixed with a suitable filler such as wood-flour, asbestos or flaked fabric. This composite powder when heated under pressure in suitable moulds first softens and takes the same shape as the mould; it then hardens into a solid compound.

The synthetic resin can also be mixed with suitable solvents to use as varnishes which are employed for impregnating electric coils, etc., for binding and insulation purposes; it is also used as a lacquer for coating painted or plain metal surfaces.

The resin is also employed to impregnate wood, paper or cloth for electrical and also decorative panels. When several layers of fabric are employed a laminated product of relatively high strength is obtained; this product has many engineering uses, to which reference is made later.

Synthetic resins of this class are also used as adhesives. It may be mentioned that the most widely employed plastic of this class is Bakelite.

Urea-formaldehyde plastics. Urea, which is made from ammonia and carbon dioxide, is used either alone or mixed with thiourea and allowed to condense with formaldehyde, the syrupformed containing from 50 to 60 per cent of synthetic resin; this syrup is used to impregnate wood-flour and similar fillers for moulding purposes.

The urea-derived synthetic resins, whilst resembling the phenol type, have the important advantage over the latter of being much more light-resistant, and they give very light coloured and light-fast moulding materials, whereas the phenolic resins are amber or brown. The urea resins can be used not only for moulding powders, but also for varnishes and the impregnation of paper or fabric sheets. Their absence of colour enables attractive semi-transparent sheets and mouldings of light pastel shades to be obtained.

The physical and mechanical properties of typical phenolic and urea formaldehyde moulding compounds, in the final set conditions, are given in Table 112.*

TABLE 112

PROPERTIES OF THERMO-SETTING PLASTICS

Properties	Phenol Formaldehyde Moulding Compounds			Urea Formaldehyde Compound Alpha Cellulose Filler
	Wood-flour Filler	Mineral Filler	Fabric Filler	
Compression ratio (bulk factor)	2·5 3·0	2·2–7·1	2·5 11·0	3·0
Specific gravity . . .	1·34 1·52	1·70–2·09	1·37–1·40	1·48 1·50
Tensile strength in lb. per sq. in.	6,000 11,000	5,000 10,000	6,500 8,000	8,000 13,000
Modulus of elasticity, lb. per sq. in. × 10^5 . . .	10 15	10 45	7 12	16
Compressive strength, lb. per sq. in.	16,000–30,000	18,000 36,000	20,000 32,000	24,000 35,000
Flexural strength in lb. per sq. in.	8,000–15,000	8,000 20,000	10,000 13,000	13,000 15,000
Impact strength, ft.-lb. . C–Charpy, I–Izod, N–Notched, U–Unnotched	0·10–0·28 I, N	0·11 0·36 I, N	0·4 2·4 I, N	0·7–1·5 C, U
Softening point (degrees C.) .	None	None	None	None
Breakdown voltage, 60 cycles, volts per mil (instantaneous)	300 500	250 400	300–450	650 720
Power factor 10^6 cycles .	0·04 0·15	0·10 0·15	0·08 0·20	....
Water absorption, immersion 24 hours	0·2–0·6	0·01 0·3	1·0–1·3	1–2

It is characteristic of all these resins that they possess high dielectric properties and in the final phase are practically insoluble in most of the known solvents; they are generally immune from attack by alkalis or acids.

These outstanding properties have led to the application of synthetic resins of this class on a very extensive scale to plastic mouldings, whereby an almost unlimited variety of shapes and sizes of finished articles can rapidly be produced. The principle employed in this method is to subject the material (in the powder or plastic form) to high pressure and heat simultaneously, whilst it is enclosed in steel moulds. Metal inserts can also be moulded in position.

* *Ante*, page 391, note.

The articles thus produced can be made rapidly and with almost perfect uniformity of shape and dimensions, with a polished finish and in practically any desired colour. They possess excellent mechanical strength and electrical properties; moreover, they are greatly superior to articles made from the best timbers.

British Standard Specification for Phenolic Materials. The British Standards Institution, in 1938, issued a Specification (No. 771) for Synthetic Resin (Phenolic) Moulding Materials and Moulding, which was the first of a series of British Standards for such materials and mouldings. It specifies the actual properties of one particular moulding powder, namely, the phenol-formaldehyde or phenolic kind, giving a classification into five special types, and the physical, mechanical, and electrical properties of each.

Bakelite Products

Bakelite is a synthetic product of wide application discovered by Dr. Baekeland when experimenting with various substances in the endeavour to find a substitute for shellac.

It was found that when equal amounts of phenol (carbolic acid) and formaldehyde (a wood distillation product) were heated together

TABLE 113

PROPERTIES OF BAKELITE MOULDING MATERIALS

	General Purpose Grades	Heat Resistant Grades	Shock Resistant Grades	Water Resistant Grades	Low Loss Grades
Specific gravity	1·31–1·45	1·7–2·0	1·35–1·40	1·7–1·9	1·7–1·9
Tensile strength (lb. per sq. in.)	5,500–7,500	4,000–6,000	5,000–7,000	5,500–7,500	4,500–6,500
Izod impact strength (cm. kgm. per sq. cm.)	1·4–1·6	1·0–20	3·4–23·0	1·4–1·6	1·2–1·9
Impact strength (ft.-lb. B.S.S. 771)	0·17–0·22	0·11–1·5	0·3–1·5	0·17–0·22	0·14–0·24
Moisture absorption (mgms. B.S.S. 771)	90–120	20–70	200–300	10–30	10–20
Electric strength at 90° C. (volts per mil)	30–150	50–120	20–100	70–120	300–400
Electric strength at 20° C. (volts per mil)	150–250	100–200	120–250	200–300	300–400
Volume resistivity at 20° C. (megohms per cm.^{3})	10^5–10^6	10^5–10^9	10^4–10^9	10^5–10^8	10^7–10^9
Surface resistivity at 20° C. (megohms per cm.^{2})	10^4–10^9	10^5–10^5	10^2–10^4	10^4–10^5	10^7–10^9
Weight per cubic inch (oz.)	0·76–0·84	0·98–1·15	0·78–0·81	0·98–1·1	0·98–1·1
Moulding contraction (inch per inch)	0·005–0·008	0·002–0·004	0·003–0·005	0·002–0·004	0·001–0·003
Bulk factor	2·3–3·0	2·2–3·1	4–15	2·3–4·0	1·8–2·5
Coefficient of thermal expansion per °C.	0·00003	0·00002	0·00003	0·00002	0·00002

in the presence of a base, an amber coloured substance was formed. This substance is soluble in alcohol and acetone; it has a melting point of about 120° F. The material in question has been given the name *Bakelite Resin "A."*

When this substance is subjected to further heat-treatment it is converted into a hard, insoluble, infusible, transparent and amber-like material known as *Bakelite Resin "C."* This is the final product employed for so many electrical and engineering purposes under the name Bakelite.

The commercial Bakelite moulding materials consist of the resin "A," mixed with various fillers under strictly controlled conditions.

It is interesting to note that although the materials employed to make Bakelite Resin "A" have characteristic pungent smells, the final product is free from any odour.

Bakelite moulding materials contain as their binding agent the synthetic resin previously mentioned.

Filling Materials

The use of filling materials such as wood-flour and asbestos in Bakelite moulding materials is for the purpose of modifying their properties and affording special colours to the finished products. Each component is included for a special purpose. For example, wood-flour is employed to give improved mechanical strength properties without affecting the lightness of the original material. Asbestos is used to give greater heat resistance.

Bakelite moulding materials are supplied commercially in powder form, ready for use in the moulds. It is strongly recommended that such powders shall be used without admixture or adulteration, and that the moulding technique recommended by the manufacturers be followed precisely.

The wood-flour materials are made in powder form, dry and granular. They soften readily and flow under the action of heat and pressure.

The standard moulding powder is made in two colours, viz. black and brown. It is also produced for special purposes in various opaque colours, such as reds, greens, yellows and grey; it can also be supplied to give wood finishes such as walnut, mahogany, rosewood, etc.

The wood-flour moulding materials give hard, sharp, moulded parts with clean lustrous surfaces, reproducing both the shape and nature of the mould surfaces with almost exact fidelity. Thus, if the mould has a highly polished surface, the mouldings will have the same finish. Each piece leaves the mould ready for use after the thin "fin" has been removed.

Inserts of all kinds can be embedded securely in the Bakelite dur-
ing the moulding process. This is a particularly advantageous property
in electrical, wireless and instrument work, for metal screws, pins,
nuts and similar items can be moulded in place so that parts when
extracted from the mould are ready for assembly or use.

In special circumstances where drilling, tapping or machining
must be done after moulding, no difficulty is experienced. Threads
of reasonable strength and accuracy can be moulded in the material.

For electrical purposes standard grades of moulding powders are
available, giving good dielectric properties, but when moulded articles
are required to withstand high temperatures, they may be stoved
after moulding at 130° C. for 48 to 80 hours.

In addition the material is odourless, non-hygroscopic, unaffected
by oil or petrol, or by exposure to temperatures up to 350° F. It will
not soften or deteriorate with age, and retains its initial colour without
fading, indefinitely.

The moulding materials are packed in airtight steel drums for
transport and storage purposes.

Bakelite, apart from its use as a wood substitute, is used as a bond-
ing medium for abrasive wheels, with emery, aloxite and carborundum.

Some Applications of Bakelite. It is impossible to mention more
than a few instances of the uses of Bakelite in the present limited space,
but special note may be made of its applications to parts hitherto
constructed from hard woods and certain metals where sufficient
numbers are required to justify the relatively expensive moulds of
the process. Its ease of moulding into complicated shapes enables it to
replace expensive fabricated or cast parts in the materials mentioned,
whilst the range of surface colours and effects, combined with the
excellent surface finish as taken from the mould, has led to its adoption
in an extremely wide field of applications.

It is employed for moulded electrical parts of complex and simple
design requiring good electrical insulation properties. Typical exam-
ples are electrical panels, radio set cases, switchgear, telephone parts,
electric fans, lighting reflectors, loudspeaker parts, small electrical
components, lighting and power sockets, plugs, connectors, terminal
blocks, electric clock cases and components, various designs of elec-
trical fittings, etc.

In automobile work it is used for instrument panels, coil-ignition
parts, mouldings, gear-lever knobs, ashtrays, cigarette lighters, insu-
lated components, number-plate housings, window frames, knobs of
controls, etc.

The armatures of dynamos and motors are impregnated with **Bakelite**

insulating varnish; this material has numerous other applications in the electrical industry. It is also used as a protective coating or lacquer for polished metal parts and for safety razor blades.

Parts of variable pitch airscrews—notably the collars—are made from a series of shaped laminations of Bakelite material. The blades themselves can be made, in hollow form, from reinforced Bakelite, moulded to shape.

Another more recent use of Bakelite is for making stereos of half-tone printing blocks, the Palaplate process of duplication being employed in this connection.

The bodies of small cameras are also being made of moulded Bakelite.

Asbestos Fibre Materials

The filler in this case consists of asbestos fibre. The moulded product is more resistant to heat and will withstand greater shock, but cannot be machined so readily. It is less resistant to mineral acids.

The following are the physical and mechanical properties of this product—

Specific gravity . . .	1·85
Weight per cubic inch . .	1·08 oz.
Coefficient of linear expansion .	0·00002 per °C.
Dielectric constant . . .	4·5–7·0
Dielectric strength . . .	150–500 volts per mil.
Tensile strength . . .	2·0–2·7 tons per sq. in.
Compressive strength . .	8·0–16 ,, ,,
Modulus of rupture (transverse strength)	6·0–13 ,, ,,

This material is supplied in the standard colours brown and black.

Flaked Fabric Moulding Material

A Bakelite moulding material introduced at a later period than those previously mentioned employs small flakes of fabric as the filler instead of wood-flour or asbestos. The resulting moulded material possesses greater shock resistance than the others mentioned, namely, as much as ten times that of ordinary moulding materials.

It is recommended particularly for such parts as hand-saw handles, handles for garden tools, switch handles and other parts having to withstand shocks.

The natural colour of the material is a mottled brown, but it can be obtained in brown or black.

Flaked fabric Bakelite parts have a specific gravity of 1·37, and tensile strength of 2·17 tons per sq. in.
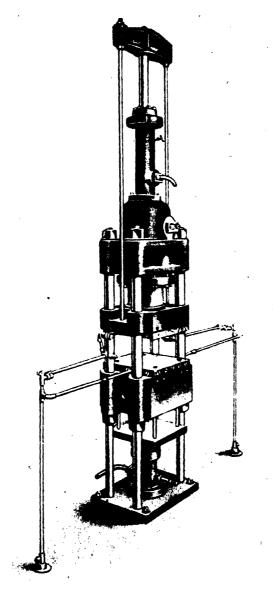
FIG. 160. SEMI-AUTOMATIC HYDRAULIC PRESS AS
USED FOR PLASTIC MOULDING

It is moulded in a similar manner to the other products, but the volume before moulding is much greater, viz. 8 : 1 instead of 3 : 1 for standard wood-flour materials.

The Moulding of Bakelite

Bakelite moulding powders require the use of mechanical, electrical and hydraulic presses fitted with suitably heated top and bottom platens. Steam is generally employed for the heating process, a steam boiler working at about 150 lb. per sq. in. being recommended.

A convenient size of press for ordinary work is one with platens measuring 12 × 12 in., with 8 in. ram and 10 in. to 12 in. stroke. A set of pumps is required to operate the hydraulic presses in cases where a large number of mouldings are to be made, but hand-operated presses are used for small quantities. Presses can be worked direct from the pumps, but the use of a hydraulic accumulator is advised as it ensures more uniform application and better control of the pressure.

The pressure required to mould Bakelite material varies from 500 to 2500 lb. per sq. in. of projected moulding area, depending upon the type of mould and shape of the moulding.

It is important that all presses should be fitted with an operating valve to control the pressure.

In almost every case it is advisable to use a comparatively light pressure until the mould is practically closed. The extreme pressure can then be exerted and maintained until the moulding is completed.

Mouldings made from Bakelite moulding material are always ejected from the hot moulds without any warping or distortion effects resulting on contact with the cooler atmosphere.

After the first moulding has been made the mould will be hot. It can be re-charged in this condition, but after being so charged it is most important that the mould should be placed under pressure as speedily as possible, otherwise the heat may cause the Bakelite material to harden and the chemical change will take place before the mould is closed. The consequence of this would be a faulty moulding and, perhaps, damage to the mould.

The time required for the mould to be under pressure varies according to the size and form of the moulding which is required to be produced.

It may, however, be generally taken as from 1½ min. for a piece weighing, say, ½ oz., with a corresponding increase of time for a moulding larger than this. This period also depends upon the temperature of the mould.

The moulds are heated, preferably, with steam at about 150 lb.
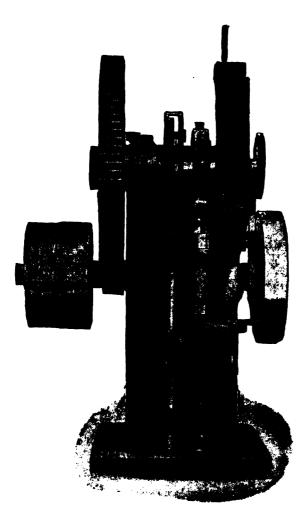
FIG. 161. ONE TYPE OF TABLETTING MACHINE
USED FOR MOULDING POWDERS

per sq. in. pressure. The temperature corresponding is between 325° F. and 375° F. The work does not suffer if left in the mould for long periods.

Tabletting

For certain types of mouldings, known as flash mouldings, it is usual to pre-form the moulding material to give round or conveniently shaped tablets, which are placed in the impression of the mould, instead of using moulding powder direct.

Special machines known as *Tabletting machines* are now available for this purpose.

Moulds

In regard to the moulds employed for Bakelite moulding materials, these vary considerably in design according to the type and shape of article to be moulded. In general there are three types of mould in common use, viz. (1) *the Flash Mould*, (2) *the Positive Flash Mould*, and (3) *the Plunger or Positive Mould*.

1. *Flash Mould.* The flash mould is suitable for multiple mouldings, and is cheaper than other types. It is usually associated with the tabletting process, and consists essentially of two parts: a top and bottom plate which come together under pressure. In most cases the impressions are separate pieces from the main plate or mould surface in order to facilitate removal of a damaged part for repair or renewal. In each of the plates the impression of the moulding required is hobbed or machined so that when the two halves come together the complete moulding is formed with a thin flash between the two plates. In this case a slight excess of material is used which forms the flash. This is necessary as the tablet or powder is not totally enclosed until the plates close up and a certain amount is pushed out. The amount lost in this way is exceedingly small, and is compensated for by the saving in time and cheaper cost of the mould construction. These moulds are easy to handle, simple to clean, and are worked with multiple impressions.

2. *Positive Flash Mould.* This type of mould is a combination of the flash and positive plunger mould, described later, with the object of using powder in conjunction with a mould low in initial cost and with multiple impressions for more rapid production. These moulds produce articles joined by a thin flash.

The impressions to be moulded are hobbed or machined out of the lower and sometimes the plunger plates. A distance piece or surrounding wall rests on the lower plate to receive the powder and
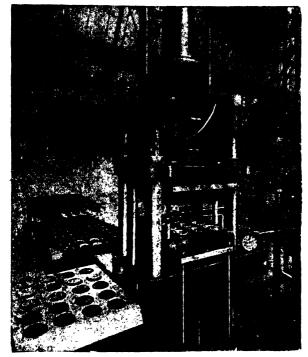
FIG. 162. STEAM-HEATED AND WATER-COOLED SEMI-AUTOMATIC
PRESS WITH MULTIPLE FLASH MOULD (G.E.C.)
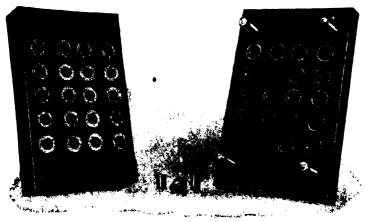
FIG. 163. A TYPICAL FLASH MOULD USED FOR
MOULDING POWDERS

enclose it. The plunger is a sliding fit into this and brings the powder under pressure. Therefore, with this type it is possible to load into the mould one bulk of powder and the plunger forces this into all the

FIG. 164. PLASTIC MOULDING PROCESS. INSERTING THE MOULDING POWDER INTO THE MOULDS

FIG. 165. PLASTIC MOULDING PROCESS. CLOSING THE MOULD, PRIOR TO APPLYING HEAT AND PRESSURE

mpressions. Consequently, by using this type of mould much weighing or measuring of powder is eliminated.

3. *Plunger or Positive Type Mould.* This type of mould consists of three or more parts, and is used exclusively in conjunction with powder as distinct from tablets. These moulds are not so low in initial cost as the flash type referred to above, but are adaptable for certain

classes of work which are impracticable with a flash mould, such as very large mouldings, where only one impression at a time is possible.

The three parts of this type of mould are: (*a*) The body of the mould; (*b*) the top tool or plunger; (*c*) the bottom tool, which is frequently used for ejecting the moulding.

(*a*) The body of the mould is made of such height as to allow the

Fig. 166.   Plastic Moulding Process.   Removing the Moulded Articles

whole of the powder to be charged into it, so that the plunger follows up the powder as it contracts.

(*b*) The plunger is made long enough to give the correct thickness to the moulding when the top of the plunger is flush with the top of the body of the mould.

(*c*) The lower tool is removable from the body of the mould and serves the purpose of ejecting the moulding.

Moulds are generally made of a good quality carbon or alloy steel, suitably heat-treated and highly polished.

The contraction allowed on mouldings is 0·006 in. per linear inch.

The ratio between the volume of powder required and that of the mould itself is about 2 : 1 ; rather more than this, however, should be allowed for the flash or spew, etc.

The Moulding Process

The actual moulding process is as follows—

The mould is heated and the powder or pre-formed tablet is fed into the mould. This is then put on the hot plate of the press and the latter closed.

It is necessary to perform this operation as quickly as possible, otherwise the powder will harden before the pressure is applied. The pressure, as previously mentioned, varies over a fairly wide range.
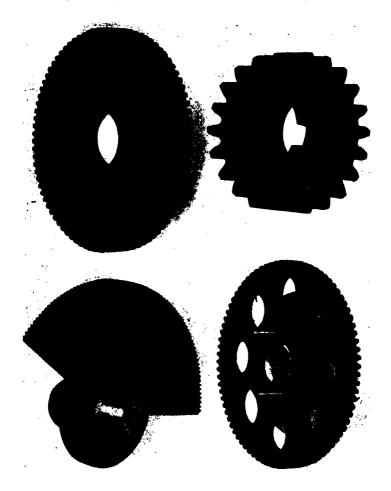
FIG. 167. EXAMPLES OF LAMINATED FABRIC BAKELITE GEARS

The time of moulding must be just long enough to ensure complete hardening of the material in the mould. The pressure should then be released and the article discharged.

The time for any given moulding varies from a few seconds to several minutes.

Bakelite Laminated

A particularly strong and serviceable form of Bakelite is now made by the application of heat and pressure upon superimposed layers of paper or fabric, impregnated with Bakelite synthetic resin

FIG. 168. EXAMPLES OF STAMPINGS IN BAKELITE LAMINATED FOR ELECTRICAL PURPOSES

The laminated sheets obtained are extremely hard, water- and heat-resisting, chemically inert and of high dielectric strength.

This material is supplied in standard sheets 50 in. × 50 in. and downwards, and in thicknesses from 0·004 in. to 2·0 in. in the case of paper impregnated sheets and from 0·008 in. to 4·0 in. in the case of the fabric material. The thinner sheets can be stamped or punched out to any desired shape for electrical laminations and similar purposes (Fig. 168).

A special grade in thicknesses from 0·010 in. to 0·125 in. is made for telephone insulation.

Bakelite Laminated is also used for radio panels and for silent pinions and gears. In the latter respect it comes into the same cate gory as fibre, rawhide, Fabroil, and similar materials, and is always employed in mesh with one or more metal gear wheels (Fig. 169).
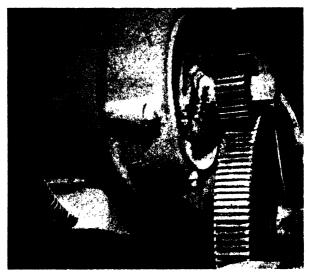
Fig. 169. Illustrating the Use of Laminated Fabric Silent Gears for Machinery Drives
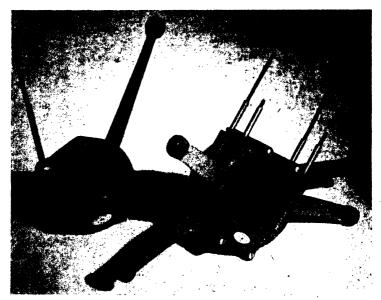
Fig. 170. Aircraft Controls using Bakelite Laminated Members

A particularly interesting application of Bakelite Laminated was that for timing gears of motor-car engines and for magnetos. It was sometimes used for the secondary or camshaft gear, in mesh with a steel gear wheel of one-half the number of teeth.

Other applications of Bakelite Laminated gears include bridge cranes, boring, planing, milling machines and hydraulic pumps.

These gears run silently, are unaffected by oil or water, and will run warm without deterioration; moreover, their life is much greater than that of steel gears.

It is unnecessary to employ metal shrouds with this material; this is an advantage from the point of view of saving gear-wheel width and cost.

In connection with the design of laminated fabric gears the same principles apply as in the case of ordinary gear wheels.

Bakelite Laminated gear material is made in thicknesses from $\frac{1}{64}$ in. up to 4 in. For gears with a larger face than 4 in. the practice is to bolt two or more pieces together to make up the desired thickness.

Sheets up to $\frac{3}{4}$ in. thick are supplied in the standard size 42 in. × 36 in. Above $\frac{3}{4}$ in. the size is 36 in. × 36 in.

The physical and mechanical properties of the several grades of Bakelite Laminated materials are given in Table 114.

The gear material may be turned, sawn, drilled, tapped, and machined in like manner to metal.*

Turning tools should be of high-speed steel, tungsten carbide or diamond cutting at a similar speed to that for bronze or cast iron.

For turning laminated synthetic material, the best tools, in order of efficiency, are the diamond, tungsten carbide-tipped steel and high-speed steel tools.

The tool bits should have no top rake and a cutting angle of 80°, with front clearance of 10°. The cut can be $\frac{1}{64}$ to $\frac{1}{8}$ in., but the feed should be 0·03 in., regardless of the cut. The cutting speeds usually range from 100 to 400 ft. per min., according to the grade of sheet, for all depths of cut.

Drilling should be done at right angles to the laminations, and the drills used should have a point angle of 50° to 60°, a slow angle of twist (or helix) and flutes as wide as possible.

For drilling parallel to the laminations a point angle of 120° should be employed.

The drilling speeds vary from 1600–1000 r.p.m. for drills up to $\frac{1}{8}$ in.

* Full particulars concerning machining and tools for Bakelite Laminated are given in a publication issued by Bakelite Ltd., London.

TABLE 114
Properties of Bakelite Laminated Materials

	Typical High-grade Paper Laminated for H.T. Insulation	Typical Ordinary Grade Paper Laminated for L.T. Insulation and Mechanical Purposes	Special Grade of Paper Laminated for Tropical Use and H.F. Insulation	Standard Type of Fabric Laminated Material for Gears and Mechanical Uses	Standard Type of Fabric Laminated Material having High Mechanical Strength
Ultimate tensile stress (lb. per sq. in.)	13,500–15,000	16,000–18,000	7,800–9,200	9,600–11,000	13,000–15,000
Shearing stress (lb. per sq. in.)	10,000–12,000	16,000–18,000	9,000–11,000	11,000–13,000	14,000–17,000
Percentage yield under 10,000 lb. per sq. in. compression	1·2–1·8	1·3–1·9	1·0–1·5	2·0–2·5	2·6–3·6
Wrapping test	65–75	35–45	110–130	15–25	15–25
Specific gravity	1·31	1·42	1·33	1·34	1·34
Weight cubic inch (oz.)	0·76	0·82	0·77	0·77	0·77
Coefficient of expansion per °C. through laminae	0·00005–0·00009	0·00008–0·00012	0·00003–0·00005	0·00007–0·00011	0·00008–0·00011
Volume resistivity (megohms per cm.^{3})	10^7–10^8	10^4–10^5	10^8	10^3–10^4	10^3–10^4
Surface resistivity (megohms per cm.^{2})	10^6–10^7	10^3–10^4	10^7	10^3–10^5	10^3–10^5
Power factor at 800 cycles (per cent)	1·5–3·5	10–20	1·5–2·5	20–40	20–40
Dielectric strength at 90° C. (volts per mil.)	200–400	40–70	300–600	30–60	30–60
Dielectric strength at 20° C. (volts per mil.)	400–600	200–300	400–700	80–120	80–120
Breakdown along laminae at 90° C.	30–40 Kv.	5–10 Kv.	70–100 Kv.	5–7 Kv.	5–7 Kv.
Dielectric constant	5·4–5·7	7·5–8·5	4·2–4·5	9–11	9–11
Moisture absorption— thickness ⅛	0·90 per cent	4·0 per cent	0·25 per cent	3·3 per cent	3·3 per cent
„ ¼	0·60 „	2·5 „	0·15 „	1·2 „	1·2 „
„ ½	0·40 „	1·7 „	0·09 „	0·75 „	0·75 „
„ 1	0·25 „	1·0 „	0·06 „	0·50 „	0·50 „

[Bakelite Ltd.. London.]

diameter to 600–100 r.p.m. for those of $\frac{1}{2}$ to 1 in. diameter. A rapid feed is recommended and an air blast to keep the drill cool.

For milling purposes high-speed steel cutters with at least six teeth per inch should be used. The cutting speeds vary with the tool design but a good guide is to use a speed of 400 ft. per min. for a 5-in. diameter by 1-in. wide cutter. The teeth should be well backed off.

Applications. Bakelite Laminated has now a wide field of application on account of its good physical and mechanical properties. Apart from its uses as a decorative and structural material for veneers and panels of buildings it has many mechanical applications, being superior to wood and metal in many instances. It is employed for bearings of heavy shafts (as previously mentioned in Chapter VII) and gear wheels : spur, helical, mitre, and herringbone gears have been cut successfully in this material.

The idler gear on the camshaft drive of gear-driven timing arrangements of petrol engines is often made of this laminated material.

In aircraft construction it is used for fairlead pulleys and guides, instrument panels, electric wiring conduit, aerial masts, supports, etc.

There are many uses for this material in electrical engineering, notably for insulated components—which are punched from the laminated sheet—telephone apparatus, and for radio apparatus, where terminal panels, valve holders, bushings, coil frames, spools, mounting platforms, etc., are made of it. The material is also used for the insulation of 132,000 volt transformers and switchgear, for electrical instruments, barriers between circuit breakers, laminated tubes for high-tension current conductors, square and rectangular tubes for insulating bus-bars, switch rocker-bars, fuse panels, railway signalling devices, electric clocks, etc.

Simple shapes can be moulded in Bakelite Laminated (fabric or paper) in steel moulds under heat and pressure; such mouldings are much stronger in tension and impact values than the ordinary material.

Synthetic-resin Bonded Fabric Sheet

The British Standards Institution Specification No. 972—1941 describes a bonded fabric sheet for mechanical and electrical purposes, made in three qualities with different numbers of threads per inch in warp and weft which has minimum tensile strengths of 14,000, 10,500 and 9000 lb. per sq. in., and cross-breaking strengths* of 20,000, 18,000 and 16,500 lb. per sq. in. respectively.

* Modulus of rupture values.

Plastics for Aircraft Purposes

In recent times a good deal of attention has been given to the use of plastic materials for aircraft constructional purposes and a certain amount of experimental work carried out, in some cases with promising results. The principal objects in view are the eventual utilization of plastics of suitable physical and mechanical properties for the production of some of the stressed parts of aircraft, notably the wings, control surfaces, fuselages and airscrews.

Whilst it is not difficult to obtain some of the desirable physical and mechanical properties, it is at present not possible to obtain the necessary combination of all the essential properties under commercial conditions of manufacture, and there remain certain difficulties to be overcome before this material can be regarded as a rival to other modern aircraft materials used for structural parts.

It has been shown in the preceding paragraphs that the strength properties of synthetic-resin plastics can be increased considerably by the addition of reinforcing materials, including wood-flour and fabric. Other materials that have been employed with promising results include cord, fine fabric, felt, cellulose fluff, paper-pulp fibre and cotton.

In this manner the tensile strength of the original synthetic resin base material, namely, 5000-6000 lb. per sq. in., can be increased to about 40,000 lb. per sq. in.; in one particular instance of cord reinforcement values up to 69,000 lb. per sq. in. have been obtained.

The usual tensile strengths of fabric reinforced resins of commercial origin range from 20,000 to 28,000 lb. per sq. in.; the compressive strengths are usually of the same order or rather higher by 10 to 15 per cent; in certain cases, however, the values are appreciably lower.

The specific gravities of reinforced synthetic resins generally lie between the limits of 1·34 and 1·38.

From the point of view of the specific strength as denoted by the ratio of tensile strength to specific gravity, several of the reinforced plastic materials compare favourably with the light high-strength alloys. Thus for a tensile strength of 24,000 lb. per sq. in. and specific gravity of 1·36, the specific strength is 17,650 as compared with 19,900 for duralumin and 19,700 for wrought magnesium alloy.

A more recent *felt base synthetic (phenolic) resin**[*]** employs fibres from the inner bark of a tree which are arranged in a manner similar to that used in paper making, the fibre length and texture being carefully controlled during manufacture. This material can be moulded into thin sheets of various shapes suitable for aircraft purposes. It has a

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[*] "Plastics and Production," S. C. Hart-Still, *The Aeroplane*, 8th November, 1938.

tensile strength of 28,000 lb. per sq. in.; compressive stress of 25,000 lb. per sq. in.; shear stress of 9000 lb. per sq. in.; and modulus of elasticity of 2.77×10^6. The 0.1 per cent proof stress value is 24,600 lb. per sq. in. The specific gravity is 1.38.

An interesting comparison between the specific strengths of certain high-strength light alloys and this felt-base plastic is given in Table 115.

TABLE 115

Specific Strengths of Aircraft Materials

Material	$\dfrac{0.1 \text{ per cent Proof}}{\text{S.G.}} \div 10^4$	$\dfrac{\text{Tensile}}{\text{S.G.}} \div 10^4$	$\dfrac{E}{\text{S.G.}} \div 10^6$	$\dfrac{E}{\text{S.G.}^2} \div 10^6$
High-grade aluminium alloy . .	2.24	1.97	3.6	—
Magnesium alloy .	0.856	1.97	3.57	1.96
Duralumin . .	1.19	1.99	3.72	1.32
Alclad . . .	1.1	1.95	3.64	1.32
Felt-base plastic .	1.78	2.03	2.0	1.45

The values in the last column on the right are included since they have a direct bearing on modern stressed skin construction; they may be used as a buckling criterion for flat panels which have the same superficial area and weight.

The results given in Table 115 indicate that the felt-base plastic compares very well with the light alloys in specific strength values, although the modulus of elasticity is appreciably lower; the specific proof stress value, however, is higher than that of the other alloys with the exception of the high-grade aluminium alloy; the 0.1 per cent proof stress and tensile strength of the latter are taken as 62,700 and 74,000 lb. per sq. in. respectively.

In connection with the possible application of the felt-base plastic for aircraft construction, some comparative values for strength and stiffness are given in Table 116; the values there given have been computed from the following relations—

$$\text{Relative Weight} = \frac{(S.G.)_2 (f_1)^{\frac{3}{2}}}{(S.G.)_1 (f_2)}$$

$$\text{Relative Stiffness} = \frac{E_2 (f_1)^{\frac{3}{2}}}{E_1 (f_2)}$$

where f is the maximum stress in the beam, E the modulus of elasticity and S.G. the specific gravity.

TABLE 116

COMPARATIVE VALUES FOR STRENGTHS OF BEAMS
(S. C. Hart-Still)

Material	Relative Weight		Relative Stiffness	
	Stressed to Ultimate Tensile	Stressed to 0·1 per cent Proof Stress	Stressed to Ultimate Tensile	Stressed to 0·1 per cent Proof Stress
High-grade aluminium alloy . .	1·0	1·0	1·0	1·0
Magnesium alloy .	1·06	1·28	1·7	2·56
Duralumin . .	1·22	1·59	1·52	2·41
Felt-base plastic .	0·96	0·92	1·03	0·97

Another promising plastic material at present in the experimental stage is *synthetic resin reinforced with fabric of flax cord type* which, in the direction of the cords, gives tensile, compressive and shear strengths of 69,400, 30,200 and 2000 lb. per sq. in. respectively. The modulus of elasticity is $7·4 \times 10^6$ lb. per sq. in., and specific gravity 1·45. With this material it is possible to obtain improved compressive strength, but at the expense of tensile strength, or reduced compressive strength with increased tensile strength and elastic modulus. The shearing strength value, namely, 2000 lb. per sq. in., is quite low, since for other reinforced plastics of lower tensile strength the values are from 6000 to 10,000 lb. per sq. in.

As a further example of a strong plastic material mention is made of *cellulose fluff impregnated with a phenolic resin* which is available initially in the form of thin cardboard sheets and then moulded under a pressure of about 2 tons per sq. in. at 150° C. The tensile strength of the board thus obtained is 22,000 lb. per sq. in.; compressive strength, 22,500 lb. per sq. in.; shear strength, 7000 lb. per sq. in.; modulus of elasticity, $2·1 \times 10^6$ lb. per sq. in.; 0·1 per cent proof stress, 12,500 lb. per sq. in.; specific gravity, 1·39.

This material has been used experimentally for moulded wings, tail planes and fuselages.

An interesting comparison between the mechanical properties of representative reinforced synthetic resins is given in Table 117.* The materials in group (A) are commercial ones; those in group (B) were specially developed for experimental airscrews; and group (C) is the previously mentioned material used experimentally in aircraft construction.

Fatigue Resistance of Reinforced Plastics. An important item that must be taken into account in considering the use of these materials for the stressed parts of aircraft is that of fatigue resistance. In this connection Dr. Gough has given the Wöhler endurance limit for a fabric reinforced synthetic resin of tensile strength 14,600 lb. per sq. in. (longitudinal) as $\pm$ 5800 lb. per sq. in. for 10,000,000 cycles; the specific gravity of this material was 1·32.

For R.R.50 wrought aluminium alloy of 2·75 S.G. the endurance limit is about $\pm$ 20,000 lb. per sq. in., so that on a weight basis this alloy is very much better than the plastic material.

Reinforced plastics possess *good damping characteristics*. In this connection the energy absorption in torsional oscillation is about twenty times that of aluminium.

The *water absorption* properties of these materials is a factor that must be considered, since any attempt to obtain high tensile strengths by reduction of the resin content is accompanied by a reduced resistance to water absorption, so that the stressed material is then liable to volumetric changes and possibly to eventual disintegration under load.

Shrinkage and Compression Allowance. In the solidification of plastic materials of the phenol-resin base type a certain degree of shrinkage occurs, so that due allowance should be made in the design and dimensions of the moulds. For materials of the Bakelite type with fillers of asbestos, very little shrinkage occurs, but for ordinary Bakelite a shrinkage allowance of 0·006 in. per linear inch should be made. Each particular moulding composition has its own definite shrinkage allowance, which for different proprietary plastics varies from 0·0025 in. to 0·008 in. per linear inch; the compression ratios employed vary from 1·8 to 1 to 3·0 to 1.

In general, reinforced synthetic resins lend themselves to speed and ease in production of aircraft parts, for complete wing and fuselage sections *are capable of mass-production*, using suitable moulds and materials. The problem of making *satisfactory joints* is one that has not been fully solved, whilst adhesion in the manner of gluing wooden parts presents certain difficulties.

* "Materials of Aircraft Construction," H. J. Gough, *Aeron. Journ.*, 1938.

TABLE 117

MECHANICAL PROPERTIES OF SOME REINFORCED SYNTHETIC RESINS

Reference	General Description	Density Lb. per ft.³	Tension Maximum Stress Lb. per sq. in.	Tension E* Lb. per sq. in. × 10⁶	Compression Maximum Stress Lb. per sq. in.	Shear Maximum Stress Lb. per sq. in.	Shear N† Lb. per sq. in. × 10⁶
A	Fabric reinforced. Square weave	84·4	10,000	1·07	26,600	6,500	0·35
		83·2	10,300	0·77	25,030	8,150	—
		85·5	12,080	1·21	27,570	10,600	0·36
		84·0	16,200	1·43	—	10,500	—
		83·1	18,000	1·53	23,000	6,500	0·39
		85·3	26,350	1·80	—	—	0·45
		85·5	28,600	1·81	—	10,600	0·30
	Cord reinforcement	86·2	23,000	5·9	15,200	3,680	—
		84·4	27,500	1·81	27,000	6,500	—
		84·4	35,000	6·9	25,000	5,000	—
	Fabric and cord reinforcement	85·6	28,600	1·8	—	7,960	—
	Bonded paper (Plane of sheet : long. dir.)	84·7	12,150	1·25	—	—	—
	(Plane of sheet : trans. dir.)	84·7	23,000	2·4	—	—	—
B	Cord reinforcement	84·0	35,000	3·5	25,000	6,000	—
		88·0	37,000	5·2	18,000	5,000	—
		90·6	55,000	5·8	23,550	—	—
		87·3	69,400	7·5	—	2,000	—
C	Impregnated cellulose fluff	86·9	22,000	2·1	22,500	7,000	—

* E—Modulus of elasticity.   † N—Modulus of rigidity.

The absence of corrosion attack in these materials and the ability to produce extremely smooth and polished surfaces—without the usual rivet heads or depressions of the metal-constructed aircraft parts—are further advantages.

In the U.S.A. certain new plastic materials, using Nylon and Saran reinforcings, are claimed to have the strength of steel, and to be suitable on a strength-to-weight basis for aircraft construction.

In connection with the use of large parts moulded from plastic materials these would require very large presses capable of producing a pressure of the order of 2000 lb. per sq. in., so that the design of these would be complicated, the sizes considerable, and the cost a heavy one.

Bakelite-faced Wooden Spars

To strengthen wood spars employed in aircraft construction a new type of Bakelite laminated material has been developed which has a wood surfacing. This wood faced laminated material is intended for use where the ends of the members are subjected to heavy shearing or bearing forces. By a special process of manufacture, the adhesion between the wood face and the core of Bakelite material is finally greater than that of the shear strength of the wood, while the wood surface itself is unaffected by any penetration of the synthetic-resin bonding material. In effect, therefore, a member so treated will retain the natural properties of wood and can be joined to other wooden members by gluing.

A typical example of one of its uses is the jointing of wing spars to the fuselage in wooden aircraft construction. Because of the liability to splitting and the low bearing strength of the wood, a large number of bolts is required. The new material, however, has a very high bearing strength, the permissible loading being 25,000 lb. per sq. in., and when inserts of the material are incorporated the strength of the joint is greatly improved to the extent, as shown by tests, that only one-half the number of bolts is required. The inserts are easily slotted into the wood members and glued in position or glued on to the outside of them.

Plastic-bonded Plywoods

Hitherto the plywoods that have been used in aircraft construction have consisted of thin veneers of selected timbers such as birch, ash, beech, etc., glued together with hide glue (used hot) or cemented with cold casein cement under pressure. The resulting plywoods,

however, were open to the serious objections of relatively low mechanical properties for their densities, variation of moisture content with consequent variation of strength properties and, in the case of casein glue plywoods, open to attack by mould (fungi) and water. Thus, the plywoods in question did not possess constant physical or mechanical properties under the conditions of usage.

These objections—which were mainly responsible for the discarding of these plywoods for aircraft stressed parts—have more recently been overcome by the use of urea-formaldehyde resins as impregnating and bonding materials; moreover, the resultant product has been shown to be of high specific strength value and permanent in character— except for very low moisture absorption which does not appear to affect the mechanical properties.

The synthetic resin may be applied in liquid form to the surfaces of the veneers or in the form of resin-soaked sheets of paper of about 0·1 mm. thickness, which are dried before placing between the veneers. The assembly is then united at 140° C. in a suitable press of the usual plywood type. The joints thus obtained are exceedingly strong and permanent. Various processes have now been developed in connection with the manufacture of plastic-bonded plywoods. These largely fall into two principal classes as follows—

(1) That in which the synthetic resin is used primarily as a binding medium for thin veneers by application as a surface layer, without previous impregnation of the wood, followed by the application of both heat and pressure.

(2) That in which rather thicker veneers are used and are impregnated with synthetic resinous material, the veneers being then assembled into layers with the grains arranged in different directions and finally heated and pressed to form permanent sheets. It is possible, by suitable arrangement of the veneer grain, selection of the number of veneers and degree of compression, to vary the strength along the length of the sheet so that beams of equal strength in bending can be produced.

In regard to the former method, owing to the lower proportion of resin to wood, the density is lower and the specific strength higher. As the resin content of the plywood is increased the density increases, so that by a suitable variation of resin the density can be altered between the limits corresponding to specific gravities of about 0·7 to 1·4.

In regard to the physical properties of such plywoods, the results given in Table 118 relate to tests* made at the Royal Aircraft

* "Laminated, Compressed and Impregnated Plywoods," W. D. Douglas, Air Ministry Report, 1938.

Establishment on seven samples of laminated birch and one of laminated beech.

TABLE 118

PHYSICAL PROPERTIES OF PLASTIC BONDED PLYWOODS

Material	Density lb. per cub. ft.	Specific Gravity	Number of Veneers per inch thickness
Solid birch	44	0·71	1
Laminated birch . . .	45·6	0·73	13*
Laminated birch . . .	54·5	0·87	50
Laminated birch . . .	56·4	0·90	49†
Laminated birch . . .	62·2	1·00	20*
Laminated birch . . .	69	1·10	34
Laminated birch . . .	86	1·38	81
Laminated beech . . .	86·9	1·39	12

The densities and mechanical strength properties of these plywoods are represented graphically in Fig. 171.‡ In connection with the density graphs shown on the left, if radial lines be drawn from the zero or origin of the two scales these will represent lines of constant specific strength, i.e. strength divided by density. Thus, the line marked xx has been drawn through the experimental value of the tensile strength of birch wood, and may be used for comparing the corresponding values of the laminated woods of curve A. The line yy refers to the specific strength of duralumin having a tensile strength of 25 tons per sq. in.

Mention may also be made of an *exceedingly strong plastic bonded plywood using hickory,* having a density of 59·7 lb. per cub. ft., and tensile, compressive and shear strengths of 36,500, 23,000 and 4600 lb. per sq. in. respectively. The elastic modulus is $6·9 \times 10^6$ lb. per sq. in.

In regard to the *fatigue resistance of these plywoods,* the latter exhibit characteristics similar to metals and ordinary woods. Thus, Wöhler tests made upon a laminated wood having a tensile strength of 30,000 lb. per sq. in., and density of 70 lb. per cub. ft., gave an endurance limit of $\pm$ 8300 lb. per sq. in. at 5×10^7 reversals of stress.

Aircraft Applications. The so-called plastic method of construction of aircraft refers to the use of plywoods using thermo-setting synthetic resins, which are moulded or formed to the required shapes

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* Veneers treated with resin in liquid form; all others with interleaved dry resin films.
† Every eighth veneer with grain transverse; all others longitudinal.
‡ *Ante,* page 415, note.

and sections by special methods which differ considerably from those employed for ordinary plastic moulding processes.

When moulding with veneer it is necessary to fit the wood into or around the mould, and to use some means of applying the plastic between the layers before pressure is applied. As a true hydrostatic condition is not established it is necessary that one-half of the mould
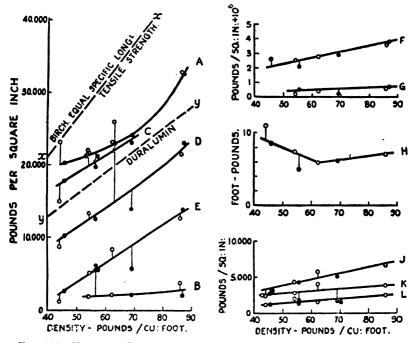
FIG. 171. TESTS ON LAMINATED COMPRESSED AND IMPREGNATED WOOD: SIX OF BIRCH, ONE OF BEECH; ALSO SOLID BIRCH

A = Ultimate tensile: Longitudinal. *B* = Ultimate tensile: Transverse. *C* = Modulus of rupture in bending. *D* = Compressive strength: Longitudinal. *E* = Compressive strength: Transverse. *F* = Young's modulus (*E*): Longitudinal; *G* = Young's modulus (*E*): Transverse. *H* = Notched bar impact. *J* = Shear strength: Longitudinal, parallel to laminations. *K* = Shear strength: Longitudinal, transverse to laminations. *L* = Shear strength: Transverse, parallel to laminations.

should be yielding, unless the parts moulded are flat or shallow; or in instances where the pressure can be applied uniformly all over the surface.

In the most favoured method the principle employed is that of an inflatable rubber bag as one of the halves of a pair of moulding disc; this method avoids the necessity of an expensive pair of matched dies.

Various patented processes which have been employed in the United States for making moulded plywood parts of aircraft, e.g. fuselages, wings, floor units and smaller components, include the Duramold, Timms and Vidal ones.* Each of these methods utilizes the rubber bag principle.

Fig. 172 illustrates a method† employed to mould the half sections of fuselages. It uses inner and outer dies of metal or wood. The inner mould is shown at *A*, the rubber bag at *B*, outer steel shell at *C* and base-plate at *D*. At *E* is indicated the pressure connection for air, steam or hot water. The shell *C* is of cylindrical shape and is bolted to the base-plate *D*. The veneer parts are cut to such tapers that each
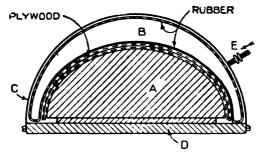
FIG. 172. METHOD OF MOULDING HALF SECTIONS OF FUSELAGES
IN PLASTIC-BONDED PLYWOOD

layer covers the preceding one completely without any overlaps. The layers are held in position by means of tacks, paper or cloth tape, steel bands or wires. The deflated rubber bag is placed over the freshly spread veneers, and the outer shell is then fitted over the whole and bolted to the base. The rubber bag is then inflated with air, hot water or steam, so that the veneers are forced together and bonded solidly; wooden frame bracing members can be inserted into suitable moulds and the plywood bonded to them at the same time as the veneers are consolidated.

In *the Duramold process* duralumin sheet metal of ⅛ in. thickness is employed. This is made possible because pressure and heat are not applied from one side only, but from all sides, by placing the entire mould and its contents and cover in a tank to which steam at 100 lb. per sq. in. pressure and 150° C. temperature is admitted. As the mould is "female" and is made very smooth on its inner surface the resulting plywood shape is also extremely smooth. The veneers usually

* Described in *Automotive Industries*, 15th January, 1941.
† "Aircraft Plywood," *Aircraft Production*, June, 1941.

employed range from $\frac{1}{20}$ to $\frac{1}{18}$ in. in thickness. The edges of the veneer strips are cemented together before the strips are set in the mould. Alternate layers of veneer are placed with their grains at right angles to those adjacent. As a rule a sheet of tissue paper impregnated with phenolic resin is placed between each layer, whilst for the outer surfaces a resin dissolved in alcohol is sprayed all over; the alcohol evaporates and leaves a coating of resin for coating purposes. Adhesive tape is used to hold the plies in position in the mould. The number of plies employed is varied over the mould area according to the
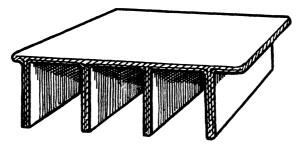
FIG. 173. AIRCRAFT FLOORING MADE OF PLASTIC-BONDED
PLYWOOD

strength requirements, so that the resulting moulded shape possesses the full strength needed at each and every section.

In view of the fact that thick sections require a longer period for the resin to melt and consolidate than thin ones, fine-wire thermo-couples are embedded in the centres of the thick sections to enable the temperature to be measured during the moulding process. When the veneers, resin and thermo-couples are in place the contents of the mould are covered with a rubber blanket and the latter is clamped to the mould at the edges in such a way that the contents of the mould are completely sealed. The air is then exhausted from the mould by means of a vacuum tap connection and the assembly is slid into the steam tank. The period of time required for moulding sections up to $\frac{3}{4}$ in. thickness in the steam tank is 10 to 12 min. The completed mould contains from 10 to 14 per cent of its weight of resin.

Aircraft parts up to 10 ft. in diameter by 20 ft. long can be made by the Duramold process. In this connection an experimental aircraft known as Model 46 Fairchild, with its fuselage made by the process in question, has made successful flights. Other experimental aircraft flown in the United States have their fuselages, control surfaces and wings made from laminated plywood.

Fig. 173 illustrates a section of aircraft flooring made by the

Duramold process. The core plies used are poplar of $\frac{1}{16}$ in. thickness. At each side of the core wood are two plies of birch, those fitting into the channels being formed in U-section with a radius at the inner corners. Flooring made in this manner weighs about 0·7 lb. per sq. ft., and is capable of supporting a distributed load of 400 lb. per sq. ft.

Other parts made by the moulded resin plywood processes include wing spars, ribs, gussets, skin coverings, wing tanks for petrol, ailerons, rudders, tail planes, elevators, pilots' seats, and airscrew blocks.

Improving the Bearing Strength of Wood

Apart from the requirements of high tensile, compressive and shear strengths for minimum weight, plywood constructions used in aircraft must also possess adequate bearing strengths at places where bolts pass through. For this purpose laminated and compressed material offer considerable advantages over plain woods. If, in addition, fabric inserts are employed at these places, a marked increase in bearing strength can be obtained. The results of tests mentioned by Dr. Gough* made upon silver spruce showed that the laminated material was 2·4 and 4·4 times as strong (according to the orientatio of the laminations) as ordinary wood, while the addition of fabric inserts raised the value to 6·4 times. For this reason composite beams and structural components are now made where the compressed wood is *reinforced locally* to withstand these shearing forces.

Hollow Moulded Airscrews

Airscrews made as hollow Bakelite mouldings represent another more recent application of reinforced synthetic resins. They possess excellent strength, resistance to corrosion, damping capacity and good fatigue resistance.

At the time of their inception these airscrew blades were the largest mouldings yet made in which continuous lengths of fabric in cord or sheet form were used. The threads at the root end forming the flange are unbroken throughout the whole length of the blade except where necessitated by the gradually reducing cross-section. A core of fusible metal is accurately located in the centre of the blade and around this the reinforced material is moulded and compressed. A high-frequency furnace is employed to melt out the core metal without damaging the blade.

A fabric treated with Bakelite resinoid, known as Texolex, has been adopted for the manufacture of cylinder, barrel and shim plate

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* *Ante*, page 415, note.

chafing rings on the de Havilland V.P. airscrew mechanism; it is also used for pistons and cylinders for the hydraulic operating gear of under-carriages and is being tried out by two hydraulic gear manufacturers for further applications in connection with hydraulic mechanisms on aircraft.

Barrel supports on the de Havilland V.P. airscrew mechanism are moulded from fabric impregnated with Bakelite resinoid. A barrel support is positioned between the spider and the barrel providing a solid support on three sides for the latter. In addition it locates the barrel so that the blade bearing rings and races do not fret against the inside face.

CHAPTER XII

RUBBER AND ITS COMPOUNDS

THE name "rubber" is given to a number of different natural gums possessing certain common properties and constituents, and also to synthetic or artificial rubbers.

The chemical designation of rubber is rather indefinite, but its synthesis shows that it belongs to the terpene series of the general chemical formula $(C_{10}H_{16})_n$. In addition, many of the crude rubbers contain proteids, resins, hydrocarbons, and other substances, which have to be removed by different processes.

The constituents of rubber are contained in the milky fluid known as *latex*, which is obtained by the incision and tapping of the bark of certain tropical trees, vines, and shrubs.

The latex, which is contained in vertical tubes or vessels in the inner bark, and which must be distinguished from the sap, has the appearance of thin cow's milk, and the crude rubber is obtained from it by the process of coagulation.

The materials employed to obtain coagulation vary with the different species of latex, and they include acetic acid, alcohol, air (fermentation process), blood, alum, lime and lime juice. Certain agents, such as heat, sunshine, and smoke, also promote coagulation. Much of the best Para rubber is obtained by exposing the latex to the smoke of burning palm-nuts.

Crêpe Rubber. This is produced from the coagulated latex by putting it through a series of powerful differentially-geared roller machines under a stream of water to wash away the impurity known as the serum. The final product consists of thin sheets with a grained or corrugated surface. These are hung in the air to dry and yield the pale crêpe rubber of commerce.

Crêpe rubber is elastic to some extent, but does not compare with the commercial rubbers produced by vulcanization with the use of fillers and accelerators. Its tensile strength may be as high as 0·5 ton per sq. in. in the best varieties.

Crêpe rubber is sometimes employed as a substitute for leather where abrasive action occurs.

The excellent abrasive resistance of raw rubber has led to its application for many engineering purposes. Thus it has been found

far more lasting than steel for the lining of ball mills and the floors of dredgers.

A sand blast which will remove $\frac{1}{16}$ in. of mild steel in a given period of time will not have any apparent effect on a suitably compounded and vulcanized rubber.

In some cases rubber is used as a binder, as in asbestos packing, 5 per cent being sufficient to hold the materials firmly together.

Purification of Rubber. The crude rubber obtained by the coagulation process is next treated to eliminate mechanical impurities by washing, the rubber being washed in hot water and then disintegrated or torn into small pieces in a special machine through which water is constantly circulated. The rubber pieces are then dried by passing through rollers, during which process they become flattened out into thin sheets.

The next process consists in mixing with the crude rubber certain substances for hardening, filling, colouring, cheapening and generally improving the rubber for its various commercial purposes. The number and the nature of the substances employed vary with the type of the crude rubber, and depend upon its intended use. Amongst the materials employed for cheapening and filling crude rubber, and at the same time improving its mechanical properties, may be mentioned sulphur, oils, resins, tars, whiting, white lead, talcs, barytes, clays, reclaimed rubber and rubber substitutes.

Fats, waxes and oils are also used to facilitate the mixing process, whilst bitumens such as tar, asphalt and pitch are employed for binding, frictioning and mixing purposes.

Pigments such as lithopone, vermilion, zinc yellow, lampblack, oxide of iron, antimony, arsenic and mercuric sulphides, graphite, etc., are incorporated with the fillers for the purpose of colouring the finished rubber product.

The black pigments available are more finely divided than the red ones giving the red rubbers, e.g. one of the sulphides of antimony. The black pigment employed consists of finely divided carbon obtained by the imperfect combustion of natural gas; it is known as *gas black*. Rubber goods containing from 10 to 20 per cent of this powder show toughness, resiliency, abrasive-resistance and energy-absorbing capacity.

Another material used in high-grade rubbers is colloidal clay prepared from China clay by a special process giving a very fine precipitate.

The more recent trend in rubber manufacture is to employ the extremely finely-divided gas black, which acts as a reinforcing agent,

in increasing proportions, so that at present it is used for the treads of automobile and aircraft tyres in percentages up to 50 of the rubber weight with improved toughness and resistance to tearing.

Conducting Rubber. By the use of a carbon black powder filler which is free from the non-conducting layer found on natural gas black, it has been possible to make rubber electrically conductive so that when used for the tyres of aircraft wheels it enables the static charge on the aircraft to be discharged to earth immediately the wheels touch the ground when landing. This rubber is also employed for the de-icing leading edges of aircraft wings, and in this application is earthed to the main metal frame system. The use of such rubber enables trailing wires and chains hitherto employed for discharging the electric charge on motor vehicles and aircraft to be dispensed with.

Incidentally, the electrical conductivity of this conducting rubber is about ten million times that of pure rubber. In the case of aircraft wheels, it is the practice to spray the inside of the wheel rim with aluminium in order to obtain good electrical contact with the metal of the rim.

Use of Reclaimed Rubber. A good deal of waste rubber, such as that obtained from old motor tyres, is used in rubber manufacture. As most goods, for example rubber tyres, are black, the bulk of the reclaimed rubber is also of this colour, so that black goods containing reclaimed rubber are more in evidence on this account. The proportion of reclaimed rubber usually advocated in the better grades of rubber is from 5 to 10 per cent.

Softeners. These are now almost universally used, as otherwise it is not possible to distribute the gas black uniformly in the rubber. The incorporation of oils and soft plastic substances with rubber must to some extent detract from the physical properties of the vulcanized product, but the benefit derived from the use of gas black and other finely divided materials much more than compensates for the 5 per cent or so of softener used to introduce it. A large number of oils or waxes are used for softeners. One of the most favoured is palm oil. Mineral oils are sometimes used; also bitumens and petroleum distillation residues. Finally, there is a large number of miscellaneous substances which may be incorporated with rubber, the commonest of which is ground rubber waste, so-called rubber substitutes (vulcanized oils), glue, etc. With the newer methods of vulcanizing, in which the temperature is kept low, a vast number of organic substances becomes available which cannot be used at the ordinary vulcanizing temperatures—one may instance ground wood (wood

flour), wood pulp, ground cork, leather waste and waste fibre of all descriptions.

Vulcanization. Most of the commercial rubbers are produced by the process of vulcanization, which consists in mixing sulphur with the rubber and heating the mixture to a temperature above the melting point of sulphur.

The sulphur combines with the rubber, the resulting compound being stronger, more elastic, and less affected by temperature changes than the pure rubber itself.

The temperature of vulcanization is about $120°$ C. to $150°$ C., but it varies somewhat with the proportion of sulphur and the grade of rubber.

About 6 per cent of sulphur, by weight, is employed in the vulcanization of the majority of articles used for mechanical purposes. For rubber shoes, coats and other black rubber goods, about 3 per cent of sulphur is used; whilst in the case of press-cured articles, such as rubber belts, about 8 per cent is embodied. Vulcanite and ebonite contain larger quantities of sulphur, and require higher temperatures (above $140°$ C. to $150°$ C.).

Vulcanized rubbers are cleaner, stronger, more stable and more elastic than crude or pure rubber.

The vulcanization process is employed commercially for the repairs of cuts in treads of tyres, for patching or repairing inner tubes, fixing new treads to worn tyres and general repairs, and building up with rubber various proprietary articles made from rubber. The grade of rubber employed must be sufficiently strong and elastic; pure Para rubber is generally used for this purpose.

Various grades of rubber are produced by the vulcanization process, the *softer grades* containing smaller amounts of sulphur and requiring lower temperatures, whilst the *harder grades* contain greater amounts of sulphur and necessitate higher temperatures.

Soft-grade rubber is used for soft packings, tubing and erasers.

Medium-grade rubber is used for a variety of commercial purposes, including rubber sheeting, canvas-ply tubing, hose piping, automobile and aeroplane tyres, balloon fabrics, shock-absorbers, surgical and other goods.

Semi-hard rubber is a hard rubber intermediate between medium-grade rubber and vulcanite; it contains more sulphur than the former grade, and is harder but not so elastic; it is used for rubber wearing surfaces, brake-blocks, buffers, etc.

Hard rubber compounds, such as *vulcanite* (red) and *ebonite* (black), contain higher proportions of sulphur and require higher vulcanization

temperatures; these materials are noted for their high insulation properties and are much employed in electrical work.

Vulcanized Rubber Articles

The usual method of vulcanizing rubber for the manufacture of articles used by engineers consists in heating it in moulds. These are made of metal, generally of steel, although sometimes aluminium and other alloys are used: copper alloys are, however, always avoided, as copper has a deleterious effect on rubber. The moulds are made in two or more parts and may be of complicated construction for an article of complex shape. A piece of the unvulcanized rubber mix, or dough, is placed in the mould which is then closed by the application of pressure either in a suitably designed press or by means of bolts. The moulds are then placed in a steam pan and heated for the correct time and temperature. Alternatively the moulds, which in this case must be provided with smooth parallel outer surfaces, are heated by being placed between the hollow platens of a press. These vulcanizing presses perform the double purpose of applying the pressure necessary to close the moulds and then the heat to vulcanize the rubber by passing steam into the hollow platens. The amount of rubber dough put into the moulds must be ascertained and kept constant by weighing, as if too little dough is put in the article will be defective and if too much there will be waste which cannot be used again unless it is reclaimed.

The cost of the mould is an important item in the final cost of rubber articles if only a small number is required. Rubber can be vulcanized without moulds, but it is not possible to obtain a hard dense product with a well-defined shape without a mould.*

Motor Tyres. The inner tube of a motor tyre is usually made by winding a sheet of rubber dough round an aluminium mandrel and then wrapping this tightly with a strip of calico wound spirally over the rubber so as to confine it during vulcanizing. The latter operation is carried out with steam under pressure. This method is also used for making rubber hose.

Ebonite

Ebonite, as previously explained, is produced as a harder rubber compound containing higher proportions of sulphur and requiring higher vulcanizing temperatures.

Mechanically, ebonite is brittle, but it can be worked, turned and

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* Fuller particulars are given in *Rubber and Engineering*. The Rubber Growers' Association, London.

polished; for turning, a high speed and sharp-edged cutting tools of high-speed tool steel or tungsten-carbide tipped are required. The tensile strength is about 1000 lb. per sq. in., and the compressive strength from 1800 to 2400 lb. per sq. in.

The specific gravity varies from 1·20 to 1·25.

Ebonite is insoluble in water, but is attacked by oils, petroleum spirits and ozone.

The resistivity of ebonite is of the order of 10^{15} to 10^{18} ohms-centimetres at ordinary temperatures, but it is readily reduced by the presence of dirt or moisture on the surface. The dielectric constant is from 1·9 to 3·5. In small thicknesses of 20 mils, the dielectric strength ranges from 1700 to 3750 volts per mil, tested between 2 in. spheres, and 1000 to 2000 volts per mil when flat electrodes are used.

The principal properties of the electrical grades of ebonite are given in Table 119.

TABLE 119

PROPERTIES OF EBONITE

Tests	"Trelleborg" Ebonite N.P.L. Tests	P.O. Quality "B"	Medium Ebonite	Poor Ebonite
Electric strength	120,000 v. per mm.	40,000 v. per mm.	36,000 v. per mm.	20,000 v. per mm.
Specific gravity	1·198	1·210	1·280	1·400
Resistivity	Infinity	Virtually Infinity	Low	Very low
Power factor	0·005	0·009	0·009	0·010
Surface leakage	None	None	Practically leak free	Leaking
Ash content	1·57%	3·00%	3·5%	5% and up

Properties of Rubber

Crude rubber is tough, pliable, solid, insoluble in water and a bad conductor of electricity; it possesses marked elastic properties which enable it to be extended or compressed through a distance equal to many times its original length, without permanent set. It is influenced by small temperature changes, and when heated it becomes soft and "tacky"; it loses most of its elasticity when placed in boiling water, but hardens and becomes elastic again upon cooling.

It melts at about 120° C. into a viscous fluid, which does not harden again. At low temperatures, most rubbers (crude, pure or commercial) lose their elastic properties and become harder; at liquid

air temperatures rubber becomes very hard and brittle and may be powdered by impact.

Crude rubber is insoluble in water and alcohol, and is only slightly affected by dilute acids, but dilute alkaline solutions exert a depoly-merizing action upon rubber, rendering it soft, or even tacky.   It is soluble in turpentine, petroleum spirits such as petrol, benzol, toluol, carbon disulphide, carbon tetrachloride and certain other liquids; solutions of crude rubber, or other grades, in some of these liquids, are used as rubber cements for pneumatic tyre repair purposes.

Crude rubber is subject to oxidation, which renders it soft and then hard and brittle; vulcanized rubber also behaves in a similar manner, but to a less marked extent, and ultra-violet rays of sunlight have a definite deteriorating effect upon rubber.

Perishing may also be due to the filling constituents of the rubber itself. Rubber goods should be stored in cool, dark places and well dusted with French chalk in order to obviate the detrimental action of grease, oils or fats that may be on the surfaces.

Physical Properties

The *electrical resistivity* of rubber is of the order of 10^{14} to 10^{16} ohms-centimetres, according to the quality, but increasing with the content of pure rubber.

The *temperature coefficient* is negative and unusually large, varying from 2 to 4 per cent, per degree C.

The *dielectric constant* of pure vulcanized rubber is from 2 to **3**, and for compounds of rubber from 3 to 4.

The *dielectric strength* of rubber varies from 300 to 500 volts per mil, and after long periods of electrification it diminishes appreciably.

The *specific gravity* of pure rubber varies from 0·93 to 0·97, and for rubber compounds from 1·7 to 2·0.

Mechanical Properties

The mechanical properties of rubber depend upon the actual grade, that is to say, upon the relative proportions of the rubber, fillers, accelerators and other ingredients.

Table 120 gives the tensile strengths, ultimate elongations, and permanent sets of six different grades of rubber, tested by the American Bureau of Standards.*

The best grades of vulcanized gas black rubber, used for their strength and elastic properties, have a tensile strength of about

* "The Testing of Mechanical Rubber Goods." Circular No. 38, U.S. Bureau of Standards.

4000 lb. per sq. in., with an·ultimate stretch of 600 per cent, that is to say, of six times their original length.

The stress-strain curve of rubber is not a straight line, as the material does not obey Hooke's Law, so that there is no true elastic modulus.

TABLE 120

THE STRENGTH PROPERTIES OF RUBBER

Grade No.	Tensile Strength, Pounds per sq. in.		Ultimate Elongation, per cent		Set,* per cent	
	Longitu-dinal	Trans-verse	Longitu-dinal	Trans-verse	Longitu-dinal	Trans-verse
1	2730	2575	630	640	11·2	7·3
2	2070	2030	640	670	6·0	5·0
3	1200	1260	480	555	22·1	16·3
4	1850	1700	410	460	34·0	24·0
5	690	510	320	280	27·5	25·0
6	880	690	315	315	34·3	25·9

For ordinary engineering purposes it is usual to take the mean slope of the stress-strain curve for a limited extension of about 200 to 300 per cent, and to estimate the elastic modulus from this mean slope value. The value for the modulus, obtained in this manner, varies from 300 to 400 lb. per sq. in. for high-grade rubbers.

The elastic modulus in compression and shear are also very low, so that rubber may be deformed to an appreciable extent by relatively small forces in all three possible methods of loading. Despite its low compression modulus it is an almost incompressible material in the same sense as water, since, if enclosed completely, it does not yield to compressive forces. When unenclosed, however, it exhibits considerable changes of shape or deformation at constant volume; thus, when stretched progressively, its cross-sectional area diminishes continually.

Rubber has to a considerable extent the characteristics of a liquid for which *Poisson's ratio* would be 0·5, for small deformations. For large deformations, however, there is a marked departure from this value, a fact which indicates that the material departs more and more from the liquid conditions.

When vulcanized rubber is subjected to a constant load of the usual values employed in engineering applications it undergoes *a continuous*

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* After 300 per cent elongation for 1 minute, with 1 minute rest. The set and the tensile strength were determined upon different samples.

deformation, which is at first rapid and then gradually decreases with time. The *shape of the stress-strain curve* will therefore depend upon the rate at which the load is applied and the period of time during which the rubber is held at any given load. Thus, a rapid load application and an early release will produce a minimum deformation, whilst
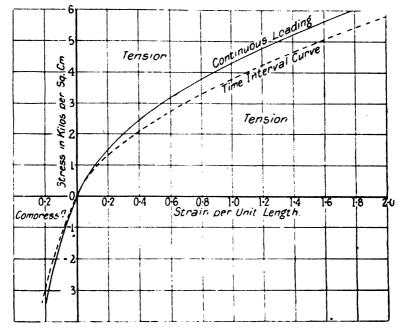
FIG. 174. STRESS-STRAIN CURVES FOR RUBBER

slow application of the load and long duration will cause **larger** deformations.

Fig. 174 shows the results of tests upon india-rubber obtained by Dr. Winkler, and indicates the lag between the stress and the strain, due to the time-interval effect.

In this connection it may be interesting to mention the results of some compression tests* upon a block of india-rubber, in which the diminution of height, or the compression strain, was noted after certain time intervals.

A compression strain of about 8 per cent at the time of loading gradually increased to about 9 per cent after the load had been **on**

* "The Measurement of Stresses in Materials and Structures," E. G. Coker, Cantor Lectures, *Roy. Soc. of Arts,* 1914.

for 4 hours, and then very slowly increased to about 9·3 per cent at the end of 26 hours. When the load was removed, the rubber recovered its original height within 1 per cent, followed by a slow recovery which, at the end of another 14 hours, brought the block within about 0·33 per cent of its original height.

Reverting again to the results shown in Fig. 174, it will also be noticed that, for the same stress value, the compression strains are smaller than the tension ones, the stress-strain curve in each case being a curved line and not a straight one.

If the elastic modulus be calculated from the ratio of the stress to the strain, the results obtained are found to be variable, due to the fact that the stress given is reckoned upon the original area, and not the actual corresponding area.

The values of the modulus, reckoned on the actual area, and the elongation per unit of stretched length, are more uniform, and the mean values for compression and tension, in the above-mentioned tests, are 195 and 162 lb. per sq. in. respectively. The maximum values for the ranges of stress taken are 222 and 373 lb. per sq. in. respectively.

Hysteresis Effect of Rubber

The most advantageous property of rubber, from the point of view of its use for springing and shock-absorbing members, is its relatively high hysteresis factor, the area of the hysteresis loop, which represents the amount of energy capable of being stored up in the material, being large.

The amount of energy absorbed by rubber is far greater than in the case of other common materials, owing to its greater stretch. Thus, good india-rubber can absorb from 500 to 1000 ft.-lb. of energy per pound weight, whereas spring steel is only capable of absorbing from 10 to 20 ft.-lb. per pound weight.

The work lost in hysteresis in low-grade rubber may be as much as 70 per cent of the work done upon the first extension. For higher grades of rubber, the hysteresis loss varies from 35 to 40 per cent.

Low-grade rubbers are not, however, suitable for shock absorbers, owing to their lower ultimate stretch, rapid deterioration properties, and relative weakness under repetitions of loading.

Tensile tests made upon rings of india-rubber, as used for shock absorbers, in general give a lower tensile strength than similar tests upon straight strips of the same material due to bending action, there being a difference in the stress between the inner and outer layers. and a change in the cross-section.

The rate of loading has only a secondary effect, provided that it is not too slow.

Temperature changes affect the results appreciably: an increase from 50° F. to 90° F. causes an average diminution in the tensile strength of about 10 per cent, with a 10 per cent increase in the elongation, and 30 per cent decrease in permanent set.

Machining of Rubber

In many grades of rubber there is a certain amount of gritty material, which tends to take the edge off cutting tools; for this reason it is necessary to use high-speed tool steels and to harden the tools to a fairly high temper.

The most suitable tool for the medium or medium-hard compositions of rubber is that with a diamond point, a little round on the point and given a sharp rake.

The speed of machining depends upon the hardness of the rubber, being slower the harder the material.

Medium-soft and soft rubber cannot be machined satisfactorily, and are therefore ground in a lathe, using an overhead drum for driving the wheel, and fixing the arbor of the wheel to the tool rest.

Alternatively, a small electric motor-driven grinder can be used and is probably more convenient.

Synthetic Rubbers

In recent years considerable progress has been made in the development of substitutes for natural rubber derived by chemical processes.

Although in practically all instances these "synthetic" rubbers are more costly to produce, the present commercial ones possess certain unique properties giving them advantages over natural rubbers. Thus, they are much more resistant to the deteriorating effects of sunlight, oxygen, heat, oil and petrol, whilst possessing most of the desirable characteristics of the natural rubbers.

Among the proprietary synthetic rubbers in present use are Neoprene, Ameripol, Buna, Chemigum, Thiokol, Koroseal, and a chlorinated rubber known as Alloprene, used as a substitute for cork and kapok.

Ameripol. This artificial rubber, made by the B. F. Goodrich Co., has proved superior to natural rubber for aeronautical and automobile purposes, notably for petrol and oil hose pipe and sparking-plug high-tension cables; in the latter connection it is able to withstand much higher operating temperatures inside engine cowlings and is almost impervious to the effects of oil and grease.

It has the same abrasive resistance and tensile strength as ordinary

rubber. The elongation, permanent set and hardness are also practically the same, although the natural rubber is definitely superior in its range of elasticity and in its low temperature resistance and tearing properties. It is, however, definitely superior in its resistance to ageing, oxidation, and heat. It is strongly resistant to the action of oil, grease, and petroleum solvents.

Neoprene is a product of the American du Pont Company and is made by polymerizing the chemical compound known as Chloropene, thus converting it into a tough rubber-like material possessing some interesting properties to which reference is made later. The original chemical employed in the process of manufacturing Neoprene is cal-cium carbide which is converted into acetylene gas (C_2H_2), which in turn is polymerized in the presence of a catalyst to form a material called mono-vinyl-acetylene; when the latter is treated with muriatic acid, chloropene is produced, which is immediately polymerized into Neoprene.

Neoprene can be treated, in manufacturing processes, in a similar manner to natural rubber, and the same technique and plant can be employed in producing various types of Neoprene rubber articles. Thus, by the incorporation of different fillers or reinforcing materials Neoprene compounds of varying physical properties can be obtained. Moreover, the finished articles of this basic material are produced by the process of vulcanization in the same way as natural rubber ones.

Unlike the latter material, sulphur is not essential to the proper vulcanization of Neoprene, although some products of this material are compounded with sulphur in order to bring out special characteristics.

The specific gravity of Neoprene is 1·25, but when compounded with reinforcing materials this figure is increased to 1·4 to 3·0.

Its tensile strength is similar to that of natural rubber as used commercially, i.e. with suitable fillers, etc., and it may be obtained with a tensile strength up to 4000 lb. per sq. in. It has similar elastic properties to ordinary rubber and its compounds can be made to show an elongation at fracture of ten times the initial length.

In regard to its physical qualities, Neoprene is inferior to natural rubber in power factor and resistivity. When uncompounded it shows about 28 per cent higher thermal conductivity than natural rubber in a similar condition; when compounded it may be to some extent considered as a heat insulator. At temperatures up to about 150° C., Neoprene rubbers have a much greater resistivity to heat than natural rubbers; the latter become soft and lose their strength, whilst Neoprene become harder and tougher.

Neoprene offers a far higher resistance to the deteriorating effect of petroleum hydrocarbons, such as petrol, paraffin and lubricating oils, than natural rubber; it is also very resistant to animal and vegetable fats and oils.

This material does not crack or perish when exposed to direct sunlight as in the case of ordinary rubber; moreover, it is less permeable to gases than the latter.

Neoprene rubber will not oxidize or age as rapidly as natural rubber, and ozone does not attack it as rapidly as the latter material
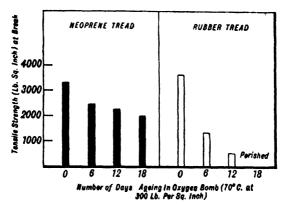
FIG. 175. COMPARISON OF AGEING PROPERTIES OF ARTIFICIAL
AND ORDINARY RUBBERS

In this connection the results of some ageing tests made with Neoprene and ordinary rubber treads of tyres in the presence of oxygen* are illustrated in Fig. 175, from which it will be observed that after twelve days' exposure the tensile strength of the Neoprene tread had fallen from about 3300 to 2300 lb. per sq. in., i.e. was reduced by 30·3 per cent, whereas that of the ordinary rubber tread had fallen from about 3600 to 600 lb. per sq. in., i.e. by about 83·5 per cent. After eighteen days the strength of the Neoprene tread had been reduced by 39·4 per cent, whereas the natural rubber tread had perished.

In connection with the resistance of Neoprene to hot mineral oil (100° C.), after twenty-one days in this oil the tensile strength fell by only 8·5 per cent with volume increase of 20 to 25 per cent, whereas ordinary rubber showed a falling off in tensile strength of about 73 per cent and volume increase of 300 per cent.

* "Synthetic Rubber." A. E. Williams, *The Engineer*. 13th September 1940.

Neoprene has been shown to have a much greater resistance to the effects of acids and alkalis than ordinary rubber.

Buna is a synthetic rubber produced originally by the I. G. Farbenindustrie in Germany, from the raw materials butadiene and sodium, as a substitute for natural rubber. *"Buna N"* is an interpolymer of butadiene and acrylic nitrile. Early in 1940 the Standard Oil Company of America acquired manufacturing rights for Buna.

In addition to its advantages in regard to resistance to oils, petrol, paraffin, sunlight and temperature increase, Buna can also be made into a hard brittle material of the ebonite class by vulcanizing with sulphur.

Chemigum. The development of synthetic rubber by the Goodyear Company over a period of fifteen years has resulted in the commercial production of several types of synthetics known as Chemigum, from which a wide range of aircraft accessories are now being made. This synthetic rubber can be compounded so as to give it a number of desirable properties for aircraft construction purposes. It can also be made very resistant to oil and petrol, to wear and abrasion; also to fire. It is superior to natural rubber in resisting oxidation and it retains its flexibility at temperatures as low as 40 degrees below zero (F.).

Chemigum is used for bullet-proof, puncture-sealing petrol and oil tanks and hose pipes, flexible connections for fuel lines, gaskets, brake seals, hydraulic control hose, pump cup packing, throw sheets for forming presses, and numerous other purposes.

Thiokol, a product of the American Thiokol Corporation, is a synthetic rubber made by condensing chlorinated ethylenes with sodium polysulphide. It is synthesized for commercial purposes from sulphur, salt and natural gas. The final product is oil-proof and unaffected by benzol, petrol or paraffin. It resists sunlight satisfactorily and will withstand heat and cold much better than ordinary rubbers; thus at 0° C. Thiokol paint spray hose shows no signs of cracking. It is probably the best of present-day synthetic rubbers in regard to resistance to aromatic solvents. Thiokol is employed largely for rubber hose as it does not swell in use. It has strong dielectric properties. Moreover, it is available in the form of moulding powders which enable oil- and petrol-proof parts to be made as readily and economically as plastic mouldings.

Du Prene is another synthetic rubber derived by chlorinating butadiene, which possesses somewhat similar properties to those previously described. It is used in the electrical industries for protective insulating jackets for high-tension wire and portable cables, e.g. the high-tension

cables for Neon signs where ozone effects would quickly perish ordinary
rubber. It is also suitable for making rubber parts of domestic elec-
trical apparatus, gaskets, washers, packing, pump pistons and cups in
oil pumps, binders for transmission belts and covers for greasy and
oily conditions.

Applications of Synthetic Rubbers

From the special properties of these rubbers, previously referred
to, it is evident that they are particularly suited to applications where
flexible rubber parts have to resist, satisfactorily, the action of oil,
grease, petrol, temperature and oxidizing agents.

Synthetic rubber is especially suited to insulation covering of
high-tension cables, since it does not crack or otherwise perish and will
withstand the engine bonnet temperatures.

In aircraft applications these rubbers are used for lubricating oil
hose, pressure grease systems, brake drum bellows, engine mountings,
gaskets, retractable undercarriage washers, ignition cables, radiator
hose and, in general, for flexible and electrical insulated conductors
liable to contact with oil, grease and also subject to heating conditions.

Synthetic rubber is also used as a protective covering for seaplane
floats, nuts, bolts and propellers as it can readily be bonded to metal.
It is employed in the production of expanded rubber for seating and
flooring on account of its fire resistance. It is more satisfactory than
ordinary rubber, in view of its better permeability, for gas containers
such as balloons and collapsible floats and aircraft dinghies.

Synthetic rubbers such as Neoprene, Buna and Thiokol have to a
large extent replaced ordinary rubber for the insulation of high-tension
cables on aircraft engines, since they will withstand the action of oil
and petrol and can be used for temperatures up to 150° C. without
protective coatings.

In aircraft strips of synthetic rubber are used for sealing the
riveted seams of hulls and floats on account of its excellent resistance
to sunlight and other corroding conditions. Neoprene has been used
for a moulded magneto gear in Pratt and Whitney engines.

Fig. 176* illustrates some of the more important artificial rubber
applications in modern aircraft. In addition to the uses already men-
tioned, this material is employed for bullet-proof petrol and oil tanks,
the leading edges of the wings, tail-plane and vertical fins (for de-icing
purposes), tyres, flexible connections for fuel lines, engine liquid
coolant hose, hydraulic control hose, brake seals, boots and cups, etc.

Although Neoprene is not such a good electrical insulator as natural

* Courtesy *Aero Digest.*

rubber, it is becoming widely used as a protective outer casing for the latter in electrical cables, more particularly those exposed to sunlight and corrosive atmospheres.

Automobile Applications of Rubber

Natural and synthetic derived rubbers are now fairly widely employed on automobiles for parts requiring vibration insulation; for
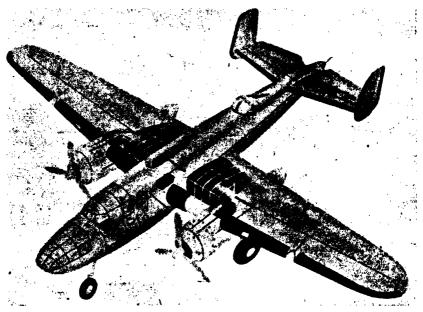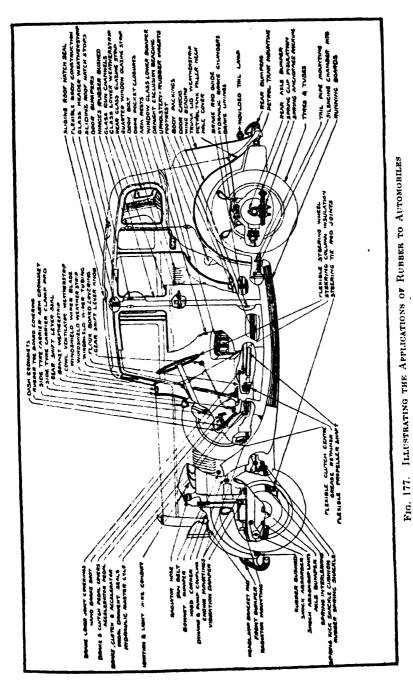
FIG. 176. ILLUSTRATING APPLICATIONS OF SYNTHETIC RUBBERS
TO AIRCRAFT PURPOSES

oil, grease and water connections and the covers of working parts—to retain the lubricants; for bearings having a limited rocking movement, such as those of spring shackle pins, for shock absorbers and spring limit stops, petrol pipe hose, oil seals for hydraulic brake pistons, propeller shaft universal couplings (of which the Layrub is a typical instance), neck hoses for petrol tank filler, petrol pump flexible diaphragms, grease covers for exposed joints, mats, gaskets, pedal covers, door silencers, beading, etc.

It has been estimated that, excluding tyres and tubes, the modern car has between two hundred and three hundred individual moulded rubber parts, and that the weight of rubber thus used varies from

FIG. 177. ILLUSTRATING THE APPLICATIONS OF RUBBER TO AUTOMOBILES

30 to 50 lb. per car according to its size. Nearly 80 per cent of the rubber produced in the United States, prior to 1940, was incorporated into motor cars, commercial vehicles, passenger vehicles and tractors.

In regard to the mechanical properties of the rubbers used in automobile and aircraft construction the following particulars are furnished by the Firestone Tire and Rubber Company—

TABLE 121

PROPERTIES OF AUTOMOBILE RUBBERS

Characteristics	High Quality Motor Support Stocks	Typical Bumper Stock
Durometer hardness (Shore type A) .	30–60	50–60
Tensile strength, lb. per sq. in. . .	2500–3500	1500–2500
Modulus at 400%, lb. per sq. in. . .	225–1800	1000–1200
Elongation at break — % . . .	600%–800%	500%–600%
*Compression set (ASTM) . . .	10%–20%	20%–30%

Engine Mountings. Originally introduced by The Chrysler Corporation, the method of insulating the engine from the chassis frame— instead of employing it as a cross-bracing member and allowing the engine vibrations to be communicated to the frame and bodywork— by means of rubber mountings, has since been adopted universally. A large number of different types of engine mountings has been used for this purpose, but the principle usually adopted is that of a three-point mounting with one rubber mounting at the front and two at the rear, with the holding-down bolts rubber-insulated from the engine and/or the frame.

Some typical examples of automobile engine mountings of the rubber-insulated pattern are shown in Fig. 178.†

Fig. 179 illustrates the Vauxhall car engine mounting which employs "Z"-shaped rubber blocks. Normally, the block assumes the shape shown at *A*, but under inclined side loads takes up the form shown at *B* such that the internal slot closes up so as to give increasing resistance as the side load is increased.

Fig. 180 illustrates a four-point mounting to the chassis frame in which individual vertical movements and a limited amount of side movement are provided for.

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* Compression set—ASTM D-395-36T constant load method. Sample— 1 sq. in. (circular) ⅛ in. thick. Load 400 lb. per sq. in.
† "Rubber and Automobiles," Colin Macbeth, *Rubber Growers' Assoc. Inc.*

FIG. 178. TYPICAL EXAMPLES OF AUTOMOBILE ENGINE MOUNTINGS

A   B

'Z' Shaped Slot in Rubber Block

'Z' Shaped Slot closed under Pressure
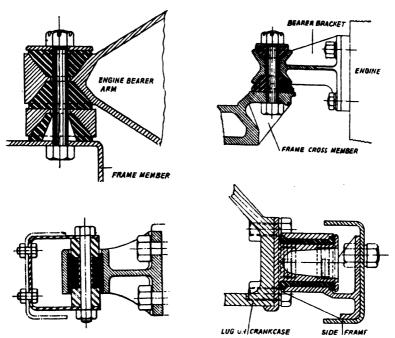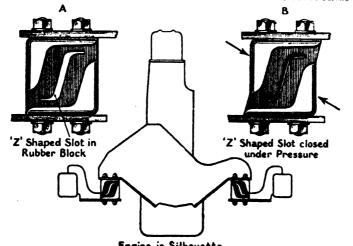
Engine in Silhouette showing Front Mounting.

FIG. 179. VAUXHALL ENGINE MOUNTINGS

Springing Systems. Rubber is employed for various parts of the springing system, such as the spring ends, shackle pins and spring movement limit stops; in the latter case, when excessive spring movements occur under severe loading conditions, the rubber blocks interposed between the springs and chassis frame come into action and take up the final impact loads.

The type of shackle pin mounting shown in Fig. 184 employs the Silentbloc stressed rubber bearings. This consists of three components,
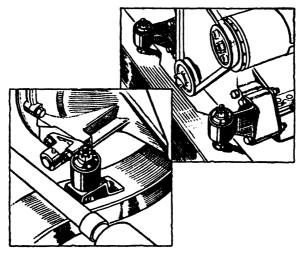
FIG. 180.   FOUR-POINT ENGINE MOUNTING
(*Above*) Front mounting.   (*Below*) One of the rear mountings.

namely, (1) rubber cylinder, (2) an internal metal bush and (3) an external metal bush. When assembled the rubber unit is stretched longitudinally in such a way that it is made to shroud the bush and enter the sleeve tightly, thus preventing longitudinal movement between the bush and sleeve. The tendency of the cylinder to contract longitudinally, being opposed by friction, is translated into a radial pressure ensuring that, unless a very great torsion is applied, there can be no slip between the rubber and other parts of the bearing. A certain amount of angular movement can occur, however, between the bush and its sleeve owing to the elasticity of the rubber. The amount of this movement depends upon the thickness of the rubber, the usual maximum allowance being 45° on either side of the neutral position.

If the angular movement allowed be exceeded slip will take place between the rubber and the sleeves with the result that the Silentbloc

will function momentarily as an ordinary bearing. It takes up a new position, however, and again functions through a given angle on either side of this new position.
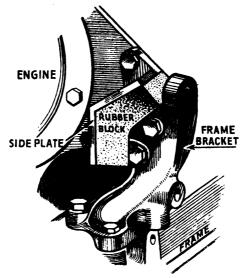
FIG. 181. ONE OF THE AUSTIN FRONT ENGINE MOUNTINGS
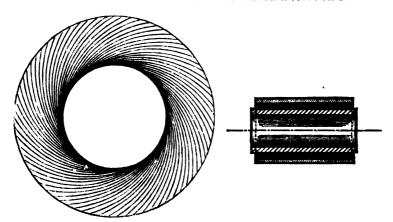
FIG. 182. ILLUSTRATING THE PRINCIPLE OF THE SILENTBLOC BEARING

It will be noted that lateral or end movement is practically impossible, although by careful design a limited amount of end movement can be obtained if it is desired.

An important point concerning this type of bearing is that the rubber gives an *air-tight* and *liquid-tight joint,* and will thus protect the bearing. Further, owing to its' resilient qualities it absorbs external

FREE STATE   DRAWN STATE

EQUAL SURFACES
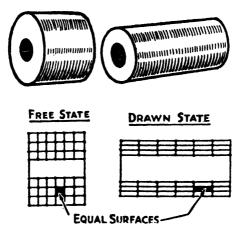
FIG. 183. SHOWING THE CONDITION OF THE RUBBER MATERIAL IN THE SILENTBLOC SYSTEM
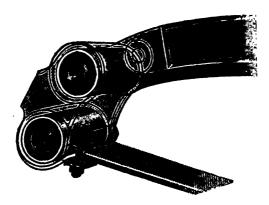
FIG. 184. APPLICATION OF SILENTBLOC BEARINGS TO MOTOR-CAR SPRING SHACKLES

vibrations. These bearings are produced in a variety of sizes suitable for loads ranging from 10 lb. up to 2 tons. If the angular movements are smaller than the standard allowance greater loads can be supported.

Applications of Silentbloc bearings include many components in automobiles. These are divided into two categories, namely—

(1) Those for *radial loads,* e.g. spring shackles, radiator support

trunnion bearings, shock absorber bearings, motor-cycle spring fork bearings, rocker arms of magneto contact-breaker, engine supports, steering and brake rod bearings, dipping headlights, etc.

(2) Those for *end thrusts*, i.e. loads applied along the axis of the bearings, combined in most cases with a rocking movement.

Other applications include the adaptation of these bearings for hinges and latches for motor-car doors, brush holders for dynamos and
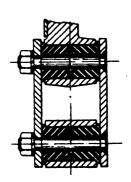
FIG. 185. RUBBER BUSHES
FOR SPRING SHACKLES
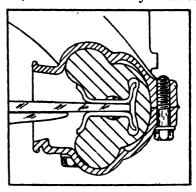
FIG. 186. RUBBER BLOCK METHOD
OF ANCHORING SPRING END

motors (permitting angular movement for replacing the brushes), and generally, in engineering work, for most rocking shaft bearings.

The bearings are usually fitted so that the outer sleeve is a force fit in its housing. The internal tube is held by bolting it up tightly on the end faces of the tube.

A type of spring blade end mounting using a moulded rubber block is shown in Fig. 186. This mounting not only provides a noiseless anchoring, but obviates the wear that normally occurs in shackle pins.

The main springing system of motor-cars has in one or two instances utilized rubber units. A typical example is that of the Firestone rubber-air suspension system shown in Fig. 187. It consists of an inflated rubber spring having rubberized fabric bellows filled with air at a pressure corresponding to the load to be carried. The bellows operate automatically in conjunction with an air reservoir by means of a pendulum shock-absorber valve; the reservoir and bellows are controlled by means of metal tubes. The device weighs about 2 lb. per wheel as compared with 15 to 20 lb. for steel springs; it has the merits of simplicity and quietness, but the bellows take up more space than the conventional springs.

Another rubber springing system, due to Colin Macbeth, employs large rubber discs of 6 to 9 in. diameter and 5 to 7 in. in overall width, which are arranged to take the car load and road shocks by torsional
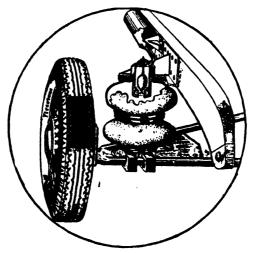
FIG. 187. RUBBER-AIR SPRINGING SYSTEM FOR AUTOMOBILES

resistance of the rubber in a similar manner to that of the steel torsion bar-springing method employed on Citroën and other cars.

Rubber interleaving of laminated steel springs is also employed on automobiles, the advantages claimed being (1) adequate friction
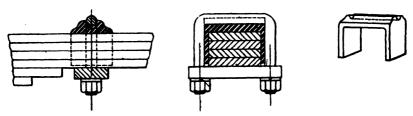
FIG. 188. ILLUSTRATING USES OF RUBBER IN AUTOMOBILE
LAMINATED SPRINGS
The rubber members are shown by the heavy black diagonal shading.

damping action which is independent of metal to metal friction, (2) elimination of the necessity of lubrication, (3) avoidance of blade squeaking, and (4) permanent and uniform springing action.

Usually tapered and flanged rubber interleaves of the same length as the steel leaves are added during assembly in a similar manner to

zinc interleaves. The squeaks that occur with laminated springs between the dry surfaces of the spring clips and the edges of the blades are overcome in some instances by the use of rubber insertions which prevent metallic contact (Fig. 188).

Universal couplings of propeller shafts between the gear-box and back axle are sometimes made with flexible rubber block members, a typical instance being the Layrub universal joint shown in Fig. 189. It consists of a flange coupling on the rear end of the gear-box driven shaft having two arms at 180° with holes, through which bolts *B* pass through the rubber blocks *A*. The two coupling flanges of the joint are at right angles and bolts connect the flanged parts to the rubber block. The inclination of the propeller shaft is taken up by the yield
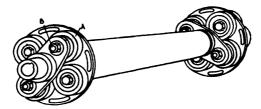
FIG. 189. THE LAYRUB UNIVERSAL COUPLING FOR AUTOMOBILE PROPELLER SHAFT

or distortion of the rubber blocks; the latter have embedded fabric on the insides of the holes and on their peripheries. This type of coupling not only runs silently, but it needs no lubrication or maintenance attention, since there are no wearing parts; further, it affords a flexible drive which insulates the gear-box from the back axle in regard to shocks and vibrations.

It is not possible to enumerate all of the various applications of rubber to automobiles, but a few further typical examples* are given in Fig. 190. In this illustration (*A*) denotes a clutch plate of the single dry-plate type with a flexible rubber centre to take up torsional shocks and vibrations. The engine crankshaft torsional vibration damper shown at (*B*) consists of a flanged steel member *A* which is bolted to the front end of the crankshaft. Between this member and the steel pulley *D* (for driving the radiator fan) rubber discs, *C*, are inserted, the latter being bolted at six intervals, by means of the bolts *B* to member *A*. A steel plate is employed between the underneath portions of the bolt heads and the left-hand rubber disc to distribute the pressure evenly.

* From "Rubber and Automobiles," Colin Macbeth, *Rubber Growers' Assoc. Inc.*
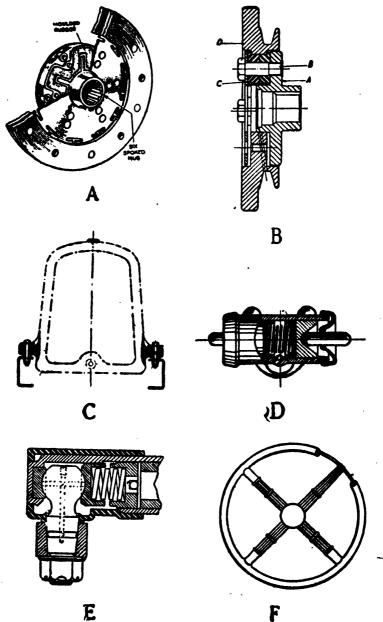
FIG. 190. TYPICAL APPLICATIONS OF RUBBER MEMBERS TO AUTOMOBILES

At (*C*) is shown a flexible radiator mounting in which rubber cylinders insulate the radiator from the chassis frame side members.

(*D*) shows a Lockheed hydraulic brake wheel cylinder member with a pair of rubber packing type pistons—between which the oil pressure for actuating the brakes is applied—and two dust retaining covers moulded in rubber; the right-hand cover and the two piston packings are shown in black.

A typical cover for retaining the grease and excluding water and dirt from the interior, in the case of a ball-joint in the connecting rod of an automobile steering system, is shown at (*E*).

The steering wheel at (*F*) employs a circular wire ring around which is moulded a tough rubber compound to form the wheel rim. The spokes forming the arms connecting the rim with the centre hub portion consist of four spring steel rods with extensions of the rubber rim to support their outer ends. This type of flexible steering wheel is favoured for sports and racing cars.

Abrasion Resistance

On account of its very high resistance to abrasion, combined with excellent resilience, rubber is used for many purposes where the question of wear is of primary importance. A notable example of this is the case of motor tyres. Here we have a material possessing good resilience, shock-absorbing properties and long wearing qualities.

Rubber is employed for flooring, as a step covering material, and to some extent as a noise reducing road surface covering. It is interesting to note that the rubber-covered steps have at least twice the length of life of stone steps.

Rubber is also used for gloves and tubing for sand-blast work, linings for ball mills, and conveyor belting for ore and coal; all of these are applications in which severe abrasion is incurred.

Rubber Associated Products

Apart from its use in the ordinary form, rubber is now widely employed in association with other materials for a variety of purposes. Used in conjunction with canvas and fabrics it preserves its flexible properties to a large extent, but is considerably stronger and will not dilate or compress to anything like the same extent as the pure rubber.

Rubber hose, belting, jointing materials for steam and hydraulic work and rubber tyres (outer covers) for cars and cycles are examples of its improved properties in association with fabrics of various kinds.

In association with asbestos, rubber forms an excellent steam band packing material. Compressed rubber and asbestos, with or without

brass wire bonding, forms a useful friction lining material for motor-car and colliery brakes and similar purposes.

Rubber hose, with both natural and artificial rubber content, is now used for many different purposes; for instance, steam, water, gas, oil, petrol, acid and vacuum hose as used for the delivery of liquids
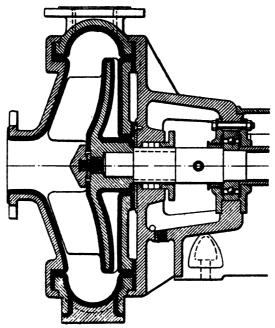
FIG. 191. CENTRIFUGAL PUMP LINED WITH RUBBER
FOR GRITTY WATER

and gases, transmission of power as in pneumatic machine connections, vacuum brake hose or sand-blast hose. Every type of hose must be considered in the light of the service it has to give. The hose may be plain or reinforced with insertions of canvas or wire.

Rubber belting is used for transmitting power and for conveying ore and other materials. In this respect its resilience and abrasion resistance are predominant features.

Rubber Linings

Rubber linings are ideal for vessels exposed to abrasion and chemical action. They can be employed for lining acid tanks, centrifuges, and tanks in which chemicals are stirred, mixed, or agitated, the blades of the stirrers being similarly covered.

Fig. 191 illustrates a centrifugal pump* used for pumping gritty water. It is lined entirely with rubber and is stated to resist the erosion of grit and pulp at least ten times more effectively than steel. The rubber, which is of a soft variety, is vulcanized on to the castings of the pump impeller and casing; the lining is about ½ in. thick.

Insulating Machinery by Rubber

An important application of rubber is in connection with the insulating of machinery vibrations from the floor or foundations. There are several methods of applying rubber for this purpose. In one a special type of foundation bolt has been

FIG. 192. COMPONENTS OF RUBBER INSULATING BOLT DEVICE

FIG. 193. THE ASSEMBLED RUBBER INSULATING BOLT DEVICE

designed, such that the bolt head is completely enclosed in rubber under compression; moreover, the degree of compression can be varied simply by tightening or slackening a screwed cap.

Fig. 192 illustrates the component parts of the insulator, whilst Fig. 193 shows it assembled ready for use. The upper portion of the flange A, which is bolted to the floor, is made in the shape of a cup or socket into which the sheet metal cup B and a thick rubber pad C are inserted. The machinery holding down bolt D has a rubber end

* International Combustion Ltd., Aldwych, London, W.C.2.

which is located within the space between A and the ring E. The lower end of D registers in the top of C. The top half of the socket fits over this pad, and may be tightened down by means of a screwed ring E engaging with the threaded base. F is an insulating washer.

These devices are placed under the feet or base of the machine to be insulated, and bolted to the floor and to the motor. The shock
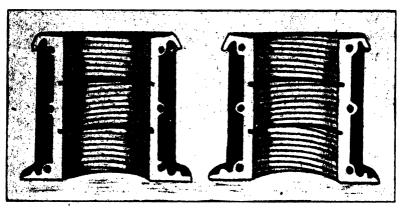
FIG. 194. RUBBER BEARINGS FOR HYDRAULIC MACHINES

insulators are then adjusted by tightening the screwed cup, whilst the machine is running, until the vibrations are all absorbed.

Rubber Bearings

A fairly recent application of rubber is for the bearings of hydraulic turbines. On account of its high abrasive resistance rubber is well suited to bearings that are exposed to the action of gritty liquids. In the case of the guide bearings of hydraulic turbines, with other materials severe silt conditions are known to cause fairly rapid wear; with rubber, however, bearings have been in use for over two years with no indications of wear. Further information on this subject is given at the end of Chapter VII.

Gravel-pumping Plant Parts

In the case of gravel-pumping plant on the Thames, delivering material into a screening plant, the sharp sand wore the elevator rollers and chain rapidly. By fitting a rubber sleeve on the drum of the roller the life of the elevator chain was prolonged at least eight months, while the rollers wore indefinitely. As the wear caused by the chain was confined to a given area of rubber, and to avoid having

to replace the whole sleeve, a number of narrow sleeves were employed; these were arranged adjacent to one another. The wet sand also cut the steel shoots rapidly; this trouble was arrested by covering them with rubber.

Some Other Engineering Applications

The use of rubber sleeves for the joints of pipe lines has also received consideration, since the use of these liquid-tight connections would not only simplify the laying of pipe lines, but also enable curved lines to be laid without the necessity for special joints.

It is also possible to protect the metal surface of pipes against erosion and corrosion by lining with rubber.

Rubber covered rollers have also been used to replace steel rollers used for guiding haulage ropes in certain South African mines. The rope, instead of bearing on a hard metal surface, rests on resilient rubber discs. These are mounted in a housing running on ball-bearings. This resilient type of roller prevents

Fig. 195. Method of Testing Bonded Rubber and Metal Member in Shear
(*Left*) Before. (*Right*) During test.

wear of the rope, has a much longer life and is less noisy in operation. Moreover, the slip that occurs when steel rollers are used—causing embrittlement of the outer strands of the cable—is absent in the case of rubber lined rollers.

Bonded Rubber and Metal

In view of the numerous applications of rubber in contact with metal parts, attention has been given to the subject of bonding rubber to metal so that the resulting parts can be used not only in compression, but also in tension and shear. It is now possible to produce commercially bonded rubber and metal which enables the rubber to be employed at will under tension, compression and shear with complete freedom to distort without volume reduction. Hitherto only the
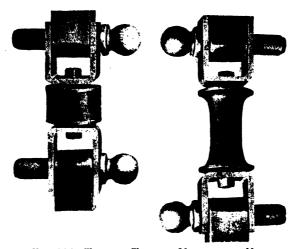
Fig. 196. Tensile Test on Metalastik Unit
(*Left*) Before. (*Right*) During test.
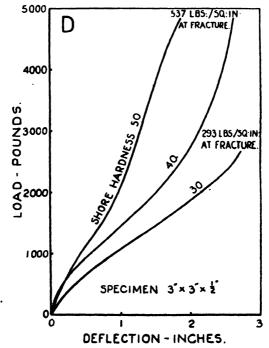
Fig. 197. Results of Shear Tests on Bonded Rubber
to Steel Specimens

natural rubber products could be bonded to metal satisfactorily, but more recently some of the synthetic rubbers, such as Neoprene, have successfully been used for this purpose.

Further, although rubber could at first only be attached to steel and cast iron, it can now be bonded satisfactorily to aluminium and magnesium alloys, Bakelite and glass.
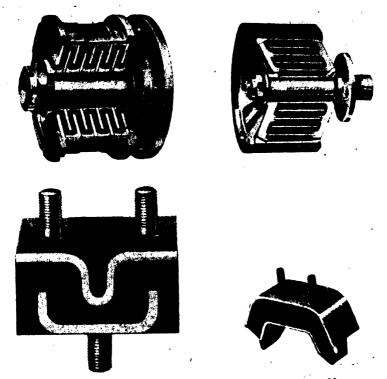
FIG. 198. TYPICAL EXAMPLES OF BONDED RUBBER ENGINE MOUNTINGS
(*Above*) Trunnion types. (*Below*) Vertical types.

When properly bonded rubber and metal joints are tested in shear, as depicted in Fig. 195, it is found that a relatively great amount of distortion can occur before the rubber fractures, and that when break-down eventually occurs the fracture does not take place at the metal surface but through the rubber itself.

The result of a tensile test made upon a Metalastik* unit is shown in the two illustrations reproduced in Fig. 196. It will be observed that

* Metalastik Ltd.

under the extreme tension conditions indicated in the right-hand illustration, namely, when the rubber has been stretched to 2·7 times its original length, there has been no separation of the rubber from the steel end discs.

Fig. 197* illustrates the results of shear tests made upon bonded rubber and steel members of three different rubber hardnesses, namely,
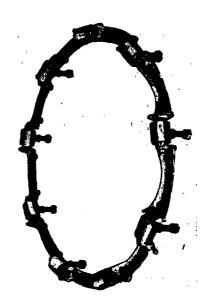
FIG. 199. THE BRISTOL RADIAL AIRCRAFT ENGINE FLEXIBLE MOUNTING UNIT

30, 40 and 50; the shear stresses at fracture were 293, 537 and 537 lb. per sq. in., respectively. Bonded rubber parts are employed for air-craft and automobile engine mountings (Fig. 198), for machinery mountings and numerous other engineering purposes.

In connection with the use of oil and petrol resisting synthetic rubbers for metal bonding purposes, a method of joining rubbers, such as Neoprene, to steel and aluminium by hot vulcanization, known as the Dura-Bond process, eliminates the need for a hard rubber base next to the brass-coated metal. This method gives an adhesive strength of 500 to 700 lb. per sq. in., and the bonded rubber can be used at temperatures up to the boiling point of water. It possesses excellent

* *Ante*, page 145, note.

age-resisting properties, and is now being used in automobile construc-
tion and in the mechanical goods industries.

The Bristol radial aircraft engines are provided with the flexible
mounting shown in Fig. 199. It consists of a ring made up of nine
rubber buffer mounting units
spaced equidistantly between
light alloy support jackets of
wide channel section. This ring
is attached to the front face of a
sheet metal cone-mounting flange
which is secured to the aircraft
frame or power unit wing-mount-
ing frame. A detailed view of
one of the rubber buffer members
is given in Fig. 200.

A

B

C

Fig. 201. The Oscillith Rubber-
steel Spring Bush

A—Insertion of member.
B—Effect of tightening nut.
C—Alternative arrangement giving greater
endwise movement.

Fig. 200. One of the Flexible
Mounting Members
(Courtesy *The Aeroplane.*)

Rubber-steel Spring Bushes

A type of resilient bush, known as the Oscillith* (Fig. 201), utilizes a
steel compressed spring firmly bonded to rubber in the form of a bush.
When the latter is compressed endwise the rubber is displaced radially
between the coils, so that the internal and external diameters are
reduced and increased respectively. The bush, which requires no

* Wilmot-Breeden Ltd.

machined parts, is slipped over a shouldered spindle of slightly smaller diameter than the internal diameter of the bush and the nut on the pin member screwed up, when the bush expands on to the pin and into the outer housing; a retaining washer is placed between the nut and bush. The latter, after insertion, is thus initially stressed and can take radial, axial and torsional loads. It is used for aircraft engine mountings, machine mountings, flexible couplings and a variety of other engineering applications.

Sponge Rubber

When a rubber compound of suitable composition is expanded by forcing an inert gas into the plastic material it can be made into the form known as expanded or sponge rubber, the constitution of which consists of an extremely large number of small gas cells enclosed by means of rubber membranes. It is thus possible to produce expanded rubber of very low density, namely, from 3 to 10 lb. per cub. ft.

This material possesses excellent elastic properties due primarily to the yielding tendencies of the numerous gas cells with their flexible rubber walls; moreover, it has a low moisture absorption; thus a sample made for aircraft purposes when soaked in water for 235 hours absorbed only 0·6 per cent of its weight of water.

Sponge rubber is used in place of kapok and horse-hair in upholstery for automobile seats and squabs, seat backs, pillows, mattresses, flooring, insulating slabs, etc.

It has been used to a small extent in aircraft construction, where it is now being bonded with synthetic resin to plywood and used as a separator.

Cellular Rubber Insulation

A more recent cellular rubber product for heat insulation purposes has only one-half the weight of cork and consists of very thin rubber-walled cells containing nitrogen. The low thermal conductivity of this insulation compares favourably with that of granulated cork, powdered gypsum and laminated fibre board. It is oil- acid- and rot-resistant and is unaffected by moisture. The product is available, commercially, in the form of insulation boards weighing 4·5 and 5·5 lb. per cub. ft., in a thickness of 1 in. The material can be sawn and planed in a similar manner to wood.

APPENDIX No. I

STRENGTH WEIGHT RATIOS OF VARIOUS MATERIALS

Material (All Wrought Condition except *)	1 Specific Gravity	2 Modulus Tons per sq. in.	3 0.1 per cent Proof Stress Tons per sq. in.	4 Maximum Stress Tons per sq. in.	5 Fatigue Limit	Ratio 3/1	Ratio 5/1
Mild steel 2S.21	7·87	13,400	15·0	32·0	±14·0	1·92	1·78
Medium carbon 35 ton 2S.1	7·86	13,300	18·0	35·0	±15·0	2·28	1·92
3¼ nickel S.69	7·87	13,050	45·0	55·0	±27·0	5·73	3·43
Special S.65	7·86	13,200	56·0	65·0	±30·0	7·14	3·82
Ni, Cr case-hardening S.82	7·87	13,100	44·0	85·0	±37·0	5·60	4·71
100 ton Ni, Cr 2S.28	7·87	13,150	72·0	100·0	±41·0	9·26	5·22
D.T.D. 46 A. S.S.R.	7·725	13,400	65·0	83·4	±36·0	8·42	4·66
D.T.D. 168 S.S.R.	7·731	13,500	60·0	80·4	±35 approx.	7·75	4·53
Copper	8·90	8,000	2·6	14·0	±3·5	0·29	0·39
Brass	8·50	8,000	5·0	20·0	±7·5	0·59	0·88
Duralumin	2·87 max.	4,510	12·0	25·0	±10·5	4·22	3·95
Super-duralumin	2·82	4,510	18·0	30·0	±12·5	6·38	4·43
Y-alloy	2·85 max.	4,825	12·0	22·0	±10·0	4·22	3·51
Al Cu alloy, 12 per cent Cu	2·90	4,920	—	9·0	±3·0	—	1·04
R.R. 56	2·85	4,920	17·0	30·0	±10·7	5·97	3·51
Magnesium alloy (Elektron)	1·82	2,800	11·5	20·0	±8·9	6·32	4·89
Ash*	0·53	630	:	3·57	:	2·25†	—
Spruce*	0·40	536	:	2·50	:	2·08†	—
Oak*	0·69	760	:	4·00	:	1·95†	—
Teak*	0·80	1,070	:	5·40	:	2·26†	—

† Proof Stress assumed one-third Maximum Stress.

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APPENDIX No. II

I. FERROUS MATERIALS, ETC.

32—1935. Steel Bars for the Production of Machined Parts for General Engineering Purposes.

51—1939. Wrought Iron for General Engineering Purposes (Grades A, B and C). [*Add.* November, 1939.]

224—1938. Steel for Die Blocks for Drop Forgings.

309—1927. White Heart Malleable Iron Castings. [*Add.* May, 1931.]

310—1927. Black Heart Malleable Iron Castings. [*Add.* May, 1931.]

321—1938. General Grey Iron Castings, Grades A and C.

592—1935. Steel Castings for General Engineering Purposes. [*Add.* February, 1941.]

681—1936. Carbon Chromium Steel.

682—1936. 3 per cent Nickel-chromium Case-hardening Steel.

725—1937. Hot Rolled Mild Steel Strip (or Hoop) not exceeding 10 inches wide for General Engineering Purposes.

762—1938. Wrought Iron Bars, "Special" Grade.

786—1938. High Duty Iron Castings, Grades 1, 2 and 3.

821—1938. Iron Castings for Gears and Gear Blanks (Ordinary, Medium and High Grade).

847—1939. Cold Rolled Mild Steel Strip for General Engineering Purposes.

858—1939. "Best Yorkshire" Wrought Iron. [*Add.* October, 1940.]

1—1920. Rolled Steel Sections for Structural Purposes. [*Under Revision,* 1940.]

13—1910. Steel for Shipbuilding, Structural. [*Under Revision,* 1940.]

18—1938. Tensile Testing of Metals.

182—184—1938. Galvanized Iron and Steel Wire.

399—400—1930/1. High and Low Carbon Steel Cylinders for Storage of Permanent Gases.

449—1937. Use of Structural Steel in Building. [*Add.* November, 1939.]

485—1934. Tests on Thin Sheet Metal and Strip [not exceeding 0·128 inch].

494—1933. Cold Drawn Weldless Steel Tubes for Steel Boilers and Superheaters.

499—1939. Welding and Cutting, Nomenclature, Definitions and Symbols for.

512—1934. Hot Finished Weldless Steel Boiler and Superheater Tubes [for Temperatures exceeding 850° Fah.].

528—1934. Lapwelded Steel Boiler Tubes for External Pressure.

548—1934. High Tensile Structural Steel for Bridges, etc. [*Add.* May, 1936, and February, 1938.]

560—1934. Engineering Symbols and Abbreviations. British Standard.

601—1935. Steel Sheets for Transformers for Power and Lighting.

621—1935. Wire Ropes of Special Construction for Engineering Purposes.

640—1935. Bare Rod or Wire Electrodes for Metal Arc Welding, Wrought Iron and Mild Steel.

641—1935. Small Rivets (Ferrous and Non-ferrous) for General Purposes.

693—1936. Oxy-acetylene Welding as Applied to Steel Structures.

933—1941. Magnetic Materials for Use under Combined D.C. and A.C. Magnetization.

968—1941. High Tensile (Fusion Welding Quality) Structural Steel for Bridges, etc., and General Building Construction.

II. AUTOMOBILE MATERIALS AND PARTS

5001—1924; 5002—1924; 5003—1927. *Cancelled.*

5004—1927. Cast Iron Piston Ring Pots (Sand Cast and Chill Cast) for Automobiles.

5005—1924. Wrought Steels for Automobiles. [*Add.* June, 1929.]

5006—1924. Cold Worked Steel Bars and Strip for Automobiles. [*Add.* June, 1928.]

5007—1924. Sheet Steels for Automobiles.

5008—1924. Valve Steels and Valve Forgings for Automobiles.

5009—1924. Steel Tubes for Automobiles.

5010—1925. Steels for Laminated Springs for Automobiles.

5015—1927. Splines (Bottom Fitting) for Automobiles, Dimensions for. [*Under Revision.*]

5016—1923; 5017—1923; 5018—1923; 5019—1923; 5020—1924; 5021 1928. *Cancelled.*

5027—1924. Magnetos for Internal Combustion Engines, Dimensions for.

5028—1924. Steel Castings (Nos. 1 and 2 Grade) for Automobiles.

III. NON-FERROUS MATERIALS, ETC.

359—1929. 98 per cent Aluminium (Notched Bars, Ingots, Rolling Slabs and Billets).

360—1929. 99 per cent Aluminium (Notched Bars and Ingots).

361—1929. 7 per cent Copper-aluminium Alloy Castings for General Engineering Purposes.

362—1929. 12 per cent Copper-aluminium Alloy Castings for General Engineering Purposes.

363—1929. Zinc-copper-aluminium Alloy Castings (Crank Cases and General Use).

385—1930. Pure Aluminium Tubes for General Engineering Purposes.

386—1930. Pure Aluminium Bars and Sections for General Engineering Purposes.

388—1938. Aluminium (Powder and Paste) for Paints.

395—1930. Wrought Light Aluminium Alloy (Duralumin) Sheets and Strips for General Engineering Purposes.

396—1930. Wrought Light Aluminium Alloy (Duralumin) Tubes for General Engineering Purposes.

414—1931. Wrought Light Aluminium Alloy Sheets and Strip (Heat-treated) for General Engineering Purposes. [Covering Y-alloy, also.]

477—1933. Wrought Light Aluminium Alloy Bars for General Engineering Purposes. [Covering Duralumin.]

478—1933. Wrought Y-alloy Bars for General Engineering Purposes.

532—1934. Light Aluminium Alloy Forgings for General Engineering Purposes. [Covering Duralumin.]

533—1934. Y-alloy Forgings for General Engineering Purposes.

7Q2—1936. Silicon Aluminium Alloy Castings for General Engineering Purposes.

703—1936. Y-alloy Castings (as Cast) for General Engineering Purposes.

704—1926. Y-alloy Castings (Heat-treated) for General Engineering Purposes.

918—1940. Aluminium Bars Containing Small Proportions of Copper and Zinc for General Engineering Purposes.

24—Part 5—1925. Railway Rolling Stock. Copper Plates, Rods, Tubes and Pipes and Brass Tubes.

99—1922. Copper Alloy Pipe Fittings. Screwed for Low and Medium Pressure B.S. Copper Tubes. [*Add*. October, 1927.]

61—1913. Copper Tubes and their Screwed Threads. (Domestic and Similar Work.)

125—1930. Hard Drawn Copper Solid and Stranded Circular Conductors for Overhead Power Transmission Purposes. [*Add*. November, 1933.]

128—1929. Bare Annealed Copper Wire for Electrical Machinery and Apparatus. Dimensions and Resistances. [*Add*. April, 1930, and November, 1935.]

174—181—1938. Overhead Line Material [Non-ferrous] for Telegraph and Telephone Purposes. [Includes Copper, Bronze and Copper-cadmium Wires.]

198—1925. Electrolytic Copper Wire Bars, Cakes, Slabs and Billets.

199—1924. Electrolytic Copper Ingots and Copper Bars.

200—1924. Tough Copper Cakes and Billets for Rolling.

201—1924. Fine Copper Cakes for Rolling.

202—1924. Electrolytic Cathode Copper.

203—1924. "Best Select" Copper.

207—1924. Special Brass Ingots for Castings.

208—1924. Special Brass Castings.

218—1925. Brass Bars and Sections, suitable for Forgings and Drop Forgings.

249—1926. Brass Bars (High Speed Screwing and Turning). [*Add*. February, 1931, and November, 1932.]

250—1926. Brass Bars, High Tensile, and Sections (Grades A and B). [*Add*. November, 1932.]

251—1927. Naval Brass (Admiralty Mixture) Bars and Sections. [*Add*. July, 1931, and November, 1932.]

252—1927. Naval Brass (Special Mixture) Bars and Sections. [*Add*. November, 1932.—*Under Revision*.]

265—1936. Cold Rolled Brass Sheets, Strip and Foil (Copper, 61·5 per cent to 64·0 per cent).

266—1936. Cold Rolled Brass Sheets, Strip and Foil (Copper, 64·0 per cent to 67·0 per cent).

267—1936. Cold Rolled Brass Sheets, Strip and Foil (Copper, 68·0 per cent to 72·0 per cent).

352—1929. Phosphor Bronze Turbine Blading.

356—1929. Brass Armouring Wire for Electrical Cables.

369—-1929. Phosphor Bronze Bars or Rods for General Purposes (Grades A and B).

378—1930. Brass Tubes and Screwed Glands for Condensers for Land Purposes.

382—1930. 2/10/88 Bronze (Gun-metal) Ingots for General Engineering Purposes.

382—1930. 2/10/88 Bronze (Gun-metal) Castings for General Engineering Purposes.

384—1930. Hard Drawn Phosphor Bronze Wire, Primarily for Armature Binding.

407—1939. Phosphor Bronze Sheets, Strip and Foil (up to 10 S.W.G.).

409—1931. Naval Brass Plates, Sheets and Strips. (Excluding N.B. Condenser Plates.)

421—1931. Phosphor Bronze Castings for Gear Blanks.

444—1932. Plain Dead Soft Copper Strip, Bars and Rods, for the Windings of Electrical Machines.

659—1936. Light Gauge Copper Tubes.

672—1936. Hard Drawn Copper-cadmium Solid and Stranded Circular Conductors for Overhead Power Transmission.

699—1936. Copper Cylinders for Domestic Purposes.

711—713—1936. Cold Rolled Brass Sheets, Strip and Foil. [Copper, 80, 85 and 90 per cent.] (Up to and including 3 S.W.G. thickness.)

837—1939. Steel Cored Copper Conductors for Overhead Power Transmission Purposes.

264—1926. Hot Rolled Yellow Metal Plates, Sheet and Strip. (Excluding Condenser Plates and Ships' Sheathing.)

885—886—1940. Seamless Brass Tubes for General Purposes (Hard Drawn, 25 to 35 Tons per sq. in. Tensile and Annealed.)

897—898—1940. Leaded Gun-metal Castings and Ingots. [*Add.* October, 1940.] [85/5 5/5.]

900—901—1940. Leaded Gun-metal Castings and Ingots. [*Add.* October, 1940.] [87 9 3 1.]

899—1940. Cold Rolled Copper Sheets and Strip (Half-hard and Annealed) for General Purposes (up to 3 S.W.G.).

920—1940. Naval Brass Die Castings.

932—1940. Brass Gravity Die Castings.

944—1941. Cast Brass Bars (suitable for Forging) and Forgings.

960—965—1941. Leaded Bronze Ingots and Castings (from 76 9/0/15 to 85/10/0/5).

IV. MISCELLANEOUS

206—1924. Silver Solder.

219—1932. Soft Solders (Grades A, B, C, D, E, F, G, H, J and K).

220—1926. Fine Zinc (or Spelter) (Grades A and B).

221—1926. Special Zinc (or Spelter).

222—1926. Foundry Zinc (or Spelter).

263—1931. Brazing Solders (Grades AA, A and B).

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